UMD-TS-148

Coastal Ocean Processes (CoOP): Cross-Margin Transport in the Great Lakes

Great Lakes Coastal Ocean Processes Workshop
Milwaukee, Wisconsin
October 6-8, 1994

J.V. Klump	University of Wisconsin-Milwaukee
K.W. Bedford	Ohio State University
M.A. Donelan	Canada Centre for Inland Waters
B.J. Eadie	NOAA, Great Lakes Environmental Research Lab
G.L. Fahnenstiel	NOAA, Great Lakes Environmental Research Lab
M.R. Roman	University of Maryland

Coastal Ocean Processes (CoOP) Report Number 5

November 1995

Technical Report

Funding provided by the National Science Foundation under Grant No. OCE-9321430, by the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory under Grant No. 40WCNR501683, and by the Office of Naval Research under Grant No. N00014-95-1-0454.

Coastal Ocean Processes (CoOP) Reports

No.

1 *Coastal Ocean Processes (CoOP): Results of an Interdisciplinary Workshop*, 1990. Contribution number 7584 from the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; 51 pp., by K.H. Brink, J.M. Bane, T.M. Church, C.W. Fairall, G.L. Geernaert, D.S. Gorsline, R.T. Guza, D.E. Hammond, G.A. Knauer, C.S. Martens, J.D. Milliman, C.A. Nittrouer, C.H. Peterson, D.P. Rogers, M.R. Roman and J.A. Yoder.

2 *Coastal Ocean Processes: A Science Prospectus*, 1992. Woods Hole Oceanographic Institution Technical Report, WHOI-92-18; 88 pp., by K.H. Brink, J.M. Bane, T.M. Church, C.W. Fairall, G.L. Geernaert, D.E. Hammond, S.M. Henrichs, C.S. Martens, C.A. Nittrouer, D.P. Rogers, M.R. Roman, J.D. Roughgarden, R.L. Smith, L.D. Wright and J.A. Yoder.

3 *Long Time Series Measurements in the Coastal Ocean: A Workshop*, 1993. Woods Hole Oceanographic Institution Technical Report, WHOI-93-49, 101 pp., by C.L. Vincent, T.C. Royer and K.H. Brink.

4 *Coastal Ocean Processes: Wind-Driven Transport Processes on the U.S. West Coast, Portland, Oregon, Workshop, July 14-16, 1993*, 1994. Woods Hole Oceanographic Institution Technical Report, WHOI-94-20, 140 pp., by R.L. Smith and K.H. Brink. October, 1994.

5 *Coastal Ocean Processes (CoOP): Cross-Margin Transport in the Great Lakes, Workshop, Milwaukee, WI, October 6-8, 1994,* 1995. Technical Report number TS-148 from the University of Maryland, Center for Environmental and Estuarine Studies, Cambridge, MD; 133 pp., by J.V. Klump, K.W. Bedford, M.A. Donelan, B.J. Eadie, G.L. Fahnenstiel and M.R Roman.

The "Relief, Drainage and Urban Areas" map on the opposite page is reproduced from *The Great Lakes: An Environmental Atlas and Resource Book*, with permission from Dr. Alun Hughes, Brock University Cartography, St. Catherines, Ontario, Canada.

Table of Contents

Executive Summary

The interface between the land and the ocean is highly dynamic. Coastal waters throughout the world are sites of intense biological, chemical and geological processing of materials arriving from both the terrestrial and offshore zones. The character of these waters, from their capacity to assimilate anthropogenic inputs, to their ability to sustain viable and healthy fisheries, or their influence on regional climate, is dictated by a complex set of oceanographic processes and forcing functions which are often unique to coastal environments. The flux of materials through this region and the transformations they undergo have not been well studied, and consequently, the ability to forecast the impact of both natural and anthropogenically-induced phenomena remains poor.

The Laurentian Great Lakes represent systems dominated by their coastal nature. While oceanographic in scale (the lakes are large enough to be significantly influenced by the earth's rotation), the lakes are, at the same time, closed basins in which the influence of coastal processes are magnified beyond that of most coastal marine systems. Nowhere is an understanding of how complex physical, chemical, biological, and geological processes interact in a coastal system more important to a body of water than in the Great Lakes. As a site for studying these processes in a generic sense, the Great Lakes offer some distinct advantages. One is size. Another is a closed basin morphology. Both make for comprehensive studies in which basin scale, mesoscale, and microscale coverage is tractable, mass balances are possible, and hydrologic budgets, flushing and water residence times are well known. Similarly, the biology is simplified. Species diversity is low and food chains are short. Variability, on the other hand, as is typical of coastal regions, is high and ecologically non-steady state conditions prevail.

Historically the lakes have been sites for some leading research in coastal hydrodynamics. In recent years, however, the Great Lakes have suffered from a lack of comprehensive studies designed to address fundamental questions concerning the biological, chemical and geological impact of coastal ocean processes. Physical limnology has fewer practitioners today than 30 years ago, despite vast improvements in the research technologies which offer the opportunity to achieve the needed understanding of such processes as coastal plumes, spill trajectories, coastal erosion and storm surges, weather effects, ice dynamics, and land-margin interactions. The CoOP Steering Committee decided that a major CoOP process study should be developed with substantial input from the combined Great Lakes and oceanographic community. The basic motivation for this effort arose not only from a series of compelling science questions but also from the realization that without such an effort, important gaps in our understanding of these lakes would remain unfilled, and our responsibility to maintain and preserve these systems into the future would be compromised.

The CoOP workshop "Great Lakes Coastal Ocean Processes Workshop" was held October 6-8, 1994, in Milwaukee, Wisconsin. The goal of the workshop was to create a document that defines a CoOP process study that would obtain a new level of quantitative understanding of the processes that dominate the transport, transformations and fates of biologically, chemically, and geologically important matter in the Great Lakes. The workshop was structured around eight working groups: Coastal Currents and Coastal Jets (Appendix 2.A.); Thermal Fronts: Vernal Dynamics and Structure (Appendix 2.B.); Upwelling and Stratified Conditions (Appendix 2.C.); Physical Dynamics of Coastal Systems and Their Relationship Among Biological, Chemical and Geological Components (Appendix 2.D.); Benthic-Pelagic Coupling in the Great Lakes: Implications for Hydrological, Solute, Sediment and Biotic Interactions (Appendix 2.E.); Air-Sea Interactions (Appendix 2.F.); Land-Margin Effects (Appendix 2.G.); and, Transformation of Solutes, Particles and Organisms (Appendix 2.H.). The workshop organizing committee drafted the CoOP Great Lakes Science Plan by synthesizing the recommendations of the eight working group reports.

Conducting a thorough suite of measurements and model formulation for every coastal region, or even every U.S. coast, is beyond the scope of the CoOP program. As described in *Coastal Ocean Processes: A Science Prospectus* (Brink et al., 1992), we assumed that there is a set of dominant processes that can be found in different mixtures in different locations. Thus the CoOP approach is to quantify key processes in a few areas well enough to model them effectively in a variety of regions.

One of the most distinctive hydrodynamic features of the Great Lakes is the pronounced seasonality in thermal stratification which results in an annually recurring sequence of physical transport regimes that dominates the movement of materials between inshore and offshore, and fundamentally impacts the biology, chemistry and geology. These different regimes, and the transition from one to the other, dictate to a large degree the nature, timing and duration of cross-margin exchange processes which, in turn, exert a major influence on biological, geological and chemical interactions at a number of important boundaries and interfaces. During isothermal periods vertical mixing is extensive, often reaching the bottom and maintaining particles and organisms (e.g., algae) in suspension, and under exposure to incident light. During vertically stratified periods, waters in contact with the bottom are largely segregated from the photic zone by a stable and persistent thermocline, through which particles are lost by settling. The presence of partial to complete ice cover, a particular feature of the Great Lakes in the winter, reduces wind stress with a concomitant reduction in mixing and light penetration, but with increased wind stress curl at the ice edge. The timing and duration of the annual transition between unstratified and stratified conditions can have a fundamental impact on the biology, chemistry and sedimentology/geology of the system in the subsequent year. Interdisciplinary, quantitative studies conducted during this period, however, are lacking.

The major basins of the Great Lakes offer diversity as well as similarity. Both cross-lake and inter-lake comparisons in proposed CoOP process studies are possible. While Lakes Erie, Michigan and Ontario have been the most extensively studied, and have the most background to aid in planning a CoOP study (e.g. the International Field Year for the Great Lakes study [IFYGL], 1972), the workshop did not arrive at a consensus with respect to a specific location or locations for study. International scientific interest from Canada through the Canada Centre for Inland Waters (CCIW), and the addition of expertise and resources of CCIW would greatly enhance any U.S. CoOP Great Lakes research program.

The central focus of a CoOP Great Lakes process study is to address the following general question:

> **What is the influence of vertical stratification on cross-margin transport of biological, chemical and geological materials in the coastal margins of the Great Lakes?**

Within this context, a number of important, process-directed issues evolved from the workshop deliberations. Interdisciplinary projects, part of a CoOP Great Lakes study, should address one or more of these specific processes.

- Storm-Induced Transport Processes: How important are the patterns and intensities of storms in the overall transport of biota and biologically, geologically and chemically important materials?
- Biological Transformations: How are differences in the composition and production of inshore and offshore plankton and fish communities maintained in an advective environment?
- Sediment-Water Interactions: What is the episodic nature of the flux of biologically, geologically and chemically important materials between the sediment and water column?
- Thermal Structure: How and to what extent are cross-barrier fluxes and biological productivity restricted by the strength of the thermocline and thermal bar?
- Jets, Meanders and Eddies: What is the role of eddy transports related to the coastal jet in the cross-margin flux of suspended and dissolved materials?

While studies in other parts of the coastal ocean significantly enhance our understanding of Great Lakes processes, not all saltwater results will apply. Some features of the Great Lakes are unique to these freshwater systems. By the same token, however, Great Lakes processes are not entirely unique and studies launched within these lakes will have broad applicability in furthering fundamental advances in coastal science in general. The cross-fertilization of marine and freshwater perspectives is deemed as a positive outcome of a Great Lakes process study. A broad based research effort, a minimum of five years in duration, with a strong emphasis on process and interdisciplinary models, and a coordinated, technologically advanced observational program is recommended.

I. Introduction

A. CoOP Background

The Coastal Ocean Processes (CoOP) effort arose from the realization within the coastal ocean science community that crosscutting, interdisciplinary research efforts were necessary to broaden our understanding of this highly dynamic and heavily utilized resource. Traditionally, coastal ocean science has been undertaken by small groups of individual investigators from one or two disciplines working to understand a specific process or region. While this traditional approach has advanced the state of our knowledge concerning specific processes, it is clear that understanding important, key linkages between the physics, chemistry, biology and geology of coastal regions can only arise from large scale, fully interdisciplinary approaches. The CoOP program was conceived in order to fill this gap with the explicit goal as defined in *Coastal Ocean Processes: A Science Prospectus* (Brink et al., 1992):

> **"to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins."**

Among the coastal waters of the United States, those of the Great Lakes represent some of the most heavily utilized, densely populated and dynamic. As a source of drinking water for some 40 million people, water quality issues within the Great Lakes are crucial to the long term well being of a large portion of the population of North America. In addition to this life support function, they serve as a economic lifeline for much of the region in areas such as international transportation, agriculture, recreation, waste assimilation and fisheries. At the same time, the Great Lakes, like their marine counterparts, have not had the benefit of large scale, interdisciplinary research programs focusing on fundamental processes. Physical oceanography of the Great Lakes may be characterized as in decline with fewer practitioners today than 30 years ago. This is despite enhanced research capabilities due to the availability of modern instruments and computing facilities, and a need for understanding such processes as coastal plumes, spill trajectories, coastal erosion and storm surges, weather effects, ice dynamics and land-margin interactions. The CoOP Steering Committee decided that a major CoOP process study should be developed with substantial input from the combined Great Lakes and oceanographic community. The basic motivation for this effort arose not only from a series of compelling science questions, but also from the realization that, without such an effort, important gaps in our understanding of how to manage and preserve these lakes would remain unfilled.

CoOP sponsored a workshop "Great Lakes Coastal Ocean Processes Workshop" held at the

University of Wisconsin-Milwaukee, Center for Great Lakes Studies and the Milwaukee War Memorial Center in downtown Milwaukee on October 6-8, 1994. This report summarizes the discussions at the workshop and presents a science plan based upon the reports of the interdisciplinary working groups at the workshop.

B. The Workshop Goal and Charge

The charge, as formulated by the CoOP Scientific Steering Committee prior to the workshop, was:

> **"to create a document that will define a CoOP process study that will obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, geologically and chemically important matter in the Great Lakes."**

The basic objectives of CoOP are to understand:

1. The quantitative mechanisms, rates and consequences of cross-margin transport of momentum, energy, solutes, particulates and organisms;
2. The atmospheric and air-sea interaction processes that affect biological productivity, chemical transformations and cross-margin solute and particulate transport;
3. The roles of transport processes that couple the benthic and pelagic zones of the continental margin;
4. The nature, effects and fates of terrestrial inputs of solutes, particles and productivity in the coastal ocean; and
5. The transformations of solutes, particulates and organisms across the continental margin.

The envisioned field study must be fully interdisciplinary and focus on the CoOP program goals. The workshop report must address the following topics:

1. What are the important, CoOP-relevant scientific problems to be addressed, and why are they important?
2. How should these problems be addressed in a cohesive, interdisciplinary manner?

Answering this question entails specific choices with their motivations and rationales for:

- geographic locations and planned observations
- substantial ideas about needed modeling and field work

- data needs
- instrumentation needs
- vessel and facilities needs
- cooperation/collaboration with other programs

3. What are the highest priority questions and approaches?

4. What are the societal implications and benefits of this study?

C. The Workshop Structure

Following approval of the CoOP Scientific Steering Committee, a committee was formed to organize a three day workshop with the goal of developing a plan for a Great Lakes CoOP study. A tentative framework and agenda were formulated based upon the previous CoOP workshop on Wind-Driven Transport Processes. The workshop was open to all interested scientists. An invitation was widely distributed via Internet and the combined mailing lists of CoOP, the International Association for Great Lakes Research, the Sea Grant Directors, and the National Association of Marine Laboratories. Approximately 116 inquiries were received and 66 individuals attended. As in the CoOP Wind Driven Processes workshop, aside from invited speakers and chair/rapporteurs, participants covered their own expenses. Prior to the workshop all participants were mailed a suggested reading list and some background information in the form of copies of the Executive Summary from *Coastal Ocean Processes: A Science Prospectus* (Brink et al., 1992), and a program proposal to the NOAA Coastal Ocean Program developed by NOAA Great Lakes Environmental Research Laboratory (GLERL) based upon a 1992 Great Lakes workshop entitled "Impacts of Event Driven Perturbations on Coastal Ecosystems".

The workshop opened in the morning with a discussion of the charge to the workshop and an overview of the CoOP program. Perspectives on coastal ocean processes in the Great Lakes were provided by four invited 25-30 minute presentations. Each of these was followed by approximately 20 minutes of open discussion by the entire group. The abstracts of these presentations appear in Appendix 1. In the afternoon, the attendees divided into four breakout sessions. Each of these work-groups focused on a different aspect of the physical dynamics and regimes of Great Lakes coastal systems with the charge to emphasize the relationships among the biological, chemical and geological components of these systems. These groups met in the afternoon and again in the morning to review their discussions. At that point the entire workshop met in plenary session for a reporting out of the working group deliberations and a general discussion. On the second afternoon, the workshop reconfigured into four new workgroups. The intent here was to focus the discussion along the lines of the important coupling mechanisms affecting transports, transformations and fates of biologically, geologically and chemically important materials in the coastal regions of the Great Lakes. Following the afternoon's deliberations the workshop met at the University of Wisconsin-Milwaukee Center for Great Lakes Studies for an informal poster session (see Appendix 6 for a list of titles). The workshop reconvened in plenary session the following mid-morning with a second reporting out/discussion session led by the workgroup rapporteurs. The workshop was concluded with a general discussion and question & answer session about the future of the program.

The Workshop Organizing Committee met with the eight working group chairs and rapporteurs to discuss the procedure, format and time-frame for producing written working group reports, shown in Appendix 2. Session chairs, in collaboration with the rapporteurs, took on the responsibility of developing an initial draft of the workgroup reports and circulating the text to the members of the group during the following few weeks. Drafts of these reports were submitted to the CoOP office and reviews solicited from scientists not in attendance. These reviews, along with comments from the organizing committee, were returned to the chairs for editing. The Organizing Committee drafted the Science Plan by synthesizing the recommendations of the eight working group reports.

II. Science Plan

A. Motivation

Conducting a thorough suite of measurements and model formulation for every coastal region even around the U.S. is beyond the scope of the CoOP program. As described in *Coastal Ocean Processes: A Science Prospectus* (Brink et al., 1992), we assume that there is a set of dominant processes that can be found in different mixtures in different locations. Thus the CoOP approach is to quantify key processes in a few areas well enough to model them effectively in a variety of regions. Nearly all coastal systems experience changes in vertical stratification that influence cross-margin transport. Because the Great Lakes are closed basins[1], lack salt, and have weak tidal currents, processes which dominate cross-margin transport are strongly influenced by the annual transition from isothermal to vertically stratified conditions.

---

[1] The Laurentian Great Lakes are a major resource to all North America, containing 20% of the world's surface fresh water and 90% of the surface fresh water of the United States (Tilzer and Bossard, 1992). They serve as the focus for multi-billion dollar tourist and recreation industry (Fed. Res. Bank of Chicago, 1991), supply 40 million people with drinking water, provide habitat for wildlife and 250 species and subspecies of fish (with an annual commercial and recreational value of approximately $4 billion (USFWS, 1990), support transportation and diverse agricultural production. The basin serves as home to 15% of the U.S. and 60% of the Canadian population. The lakes are a highly managed system, with eight states, several federal agencies, one provincial government, and international treaties all playing a role.

Seasonality, driven by the annual cycle in solar radiation and therefore energy and heat inputs, is a dominant feature of most temperate coastal environments. Annual temperature oscillations of up to 25-30° C are not uncommon, and solar energy fluxes vary by three- to four-fold. Wind forcing and other external perturbations are additional layers of complexity laid on the background of this heating cycle. Many biological, geological and chemical rate functions are exponentially related to temperature and light. A CoOP study which focuses on a system with pronounced seasonal effects would provide valuable insight into similar patterns and dynamics over a broad range of systems.

Characteristic features of the Great Lakes

The overriding feature of the physical dynamics of the Great Lakes is the annual transition between vertically well mixed conditions and vertically stratified conditions. These different regimes, and the transition from one to the other, dictate to a large degree the nature, timing and duration of cross-margin exchange processes which, in turn, exert a major influence on biological, geological and chemical interactions at a number of important boundaries and interfaces. During isothermal periods each lake consists of a vertically well-mixed fluid which contacts the bottom and also maintains particles and organisms (e.g., algae) in suspension, and, therefore, exposed to incident light. During vertically stratified conditions, waters in contact with the bottom are segregated from the photic zone by a stable and persistent thermocline, through which particles are lost by settling. The timing of this annual transition has a fundamental impact on the biology, chemistry and sedimentology/geology of the system during the subsequent year.

The lakes exhibit a generally low energy current regime during periods of relative calm, i.e. mean flow <5 cm sec^{-1}. The same is true of the wave field. Consequently, the lakes' response to the wind is relatively large as compared to a wind driven coastal shelf environment, because both the current and wave fields in the lakes spin up from a relatively low background state. The difference between quiescent and wind event perturbed conditions is therefore high and generates a high "signal to noise" ratio for any particular event.

Wind events sufficient to disturb nearshore conditions of the Great Lakes occur approximately every 5-7 days during winter, spring and fall, and approximately every 7-10 days in summer. These events are typically short-lived, with backing and veering of wind direction, often in less than a day. Consequently, within these events there are no persistent wind directions or speeds, and both spin-up and decay of nearshore physical dynamics are rapid and nonlinear. Prevailing winds, however, can produce rather common features such as upwelling on the eastern and northern shores of Lakes Michigan and Ontario, and downwelling on the opposite shore. Since the density structure is controlled almost entirely by the temperature structure, cooling events can mix the entire water column.

The Great Lakes are also closed basins, with fairly simple, elliptical geometries in the case of

Lakes Michigan, Erie and Ontario, resulting in a double-sided boundary condition atypical of most oceanic coastal systems. The lakes are large enough, however, to come under the influence of the earth's rotation. Boundary processes are often linked across the basin. For example, upwelling on one side is often coincident with downwelling on the opposite side. Both internal and surface seiches propagate in all of the lakes, both transversely and longitudinally. While lunar tides are small (<20 mm), surface seiches can be significant. For example, the surface seiche in Lake Erie can reach an amplitude in excess of 2 meters with a period of approximately 14 hours. During stratified conditions, internal seiches can cause oscillations of the thermocline with much greater amplitude (>10 m in Lake Michigan) and period, as well as significant horizontal currents near nodal points.

One particularly useful consequence of a closed basin geometry is that biological, geological, chemical and physical budgeting is greatly simplified. In general, the lakes have a single outflow and, in some cases, one major inflow which derives from the "upstream" system. Moreover, hydrologic budgets, flushing and water residence times are well known, with historical records approaching 130 years.

A special feature of the lakes is the existence of partial to complete ice cover during winter. Whereas Lake Erie often freezes over completely in winter, the other lakes have historically had significant ice cover (>50%) only in extreme cold years (approximately 1 year in 25). The presence of ice cover reduces wind stress with a concomitant reduction in mixing and light penetration, but with increased wind stress curl at the ice edge. Ice scour can be an important mass transport process, and is of major concern owing to its potential for coastal erosion and shoreline damage.

A major ecological characteristic of the lakes is their susceptibility to invasion by exotic species (e.g., the lamprey eel, alewife and zebra mussel, to mention just a few), and the role that non-indigenous species (including, e.g., stocked salmon) currently play within the system. Ecologically the lakes have changed extensively in the last 100 years, and all have seen dramatic changes within the last decade. The result is a biologically non-steady state system that confounds predictive ecological modeling and resource management.

The definition of "cross-margin" in CoOP terms, invoking the relationship between the inshore and offshore, is not a simple one in the Great Lakes. This differentiation is dependent upon a variety of factors, including season, location, weather events, topography, and the particular phenomenon under study. In winter, the margin may be defined as the offshore edge of shore-fast ice sheets, where formed. In spring, it is the offshore-migrating thermal front. In summer, it is the outer edge (about 20 km or 5 Rossby radii from shore) of the shore-parallel strip within which upwelling/downwelling events occur and within which shore-parallel currents dominate. Offshore, Ekman drift, rotating inertial currents, and internal waves dominate. Another type of "margin" is the depth contour above which storm waves occasionally resuspend sediments. Other margins are regions where "shelves" merge into "slopes"; but these typically marine features are not universally present in the lakes.

Why is a Great Lakes CoOP Study needed?

While studies in other parts of the coastal ocean can significantly enhance our understanding of Great Lakes processes, not all saltwater results will apply. Some features of the Great Lakes are unique to these freshwater systems. However, Great Lakes' processes are not entirely unique, and studies launched within these lakes will have broad applicability in furthering fundamental advances in coastal science in general. The cross-fertilization of marine and freshwater perspectives is an additional benefit of a Great Lakes process study. The need for such a study derives from a number of compelling science questions.

- By virtue of the bounded nature of the Great Lakes basins, the intimate connection between the land and the lakes, and their physical scale as seas, "coastal processes" play a dominant role in structuring the ecosystem of the Great Lakes. Virtually no part of these lakes is unaffected by processes occurring within the coastal margin and, indeed, much of the hydrodynamic structure of the lakes is dictated by the existence of coastal boundaries. Our current knowledge of the processes which occur at these boundaries is particularly weak in two fundamental ways: how they link to the biology, and how they interact with the annual sequence of mixing and stratification.

- Despite the importance of the winter-summer (isothermal-stratified) transition, data collection and studies during this period have been very limited. This is due, in large part, to the logistical difficulties of winter operations, when ice cover, extreme cold, severe icing conditions, and frequent storms make operations difficult and hazardous.

- The pattern and duration of frequent storm fronts generate highly dynamic coastal current, wave, and riverine plume fields. One consequence of such storms is the rapid spin-up, decay, reversal and resonance of advective events. These interactions are poorly known and highly nonlinear.

- Productivity, as well as factors impacting production (inter-annual and intra-annual) in the lakes, have not been well studied, particularly during the winter-summer transition. The spatial patchiness in production and its coupling to physical processes is even less understood, though very important. Much of our information in this regard derives from satellite images depicting significant onshore-offshore and alongshore gradients in optical properties, on length scales of kms to 10's of kms.

- While a great deal is currently known about the permanent accumulation of sediments in the depositional areas of the lakes (particularly Michigan and Erie), few data exist concerning the mechanisms and timing of processes that deliver these materials from the land-margin boundary, through the coastal margin, and into deep regions of the lake bed where they are buried. It is known that these processes are moving and focusing sediments and their associated constituents, like contaminants, on a time scale of decades, but the underlying mechanisms have not been investigated quantitatively. Since these systems are largely closed basins with water residence times varying from three years (Erie) to nearly 200 years (Superior), the sediments within each basin represent a major repository of externally supplied constituents, e.g., nutrients and contaminants, that have accumulated over time.

- Sediment-water interactions are a key component of cycling of biologically, geologically and chemically important materials in shallow systems with rapid vertical settling rates. While the importance of sediment-water interactions are well recognized, the exact mechanisms, timing and fluxes are not known quantitatively, particularly during well mixed conditions. Mass balance considerations imply that sediments are a large source of recycled nutrients which fuel primary production, but the mode of coupling has not been described. Given the dimictic nature of the system (two overturns annually), the interaction of surface waters with the bottom is limited, during stratified conditions, to coastal upwelling events. These inject hypolimnetic waters into the photic zone with an unknown degree of mixing across the upwelled water/epilimnetic water front.

- Ice cover and its effects on the entire range of physical and biological, geological and chemical properties of the lakes have been incompletely studied. Data on the extent and duration of ice cover from satellites are excellent, as are surface temperature data. While not unique to the Great Lakes, the existence of ice cover is in contrast to many "typical" coastal settings.

- Inshore-offshore gradients in the distribution of biological activity and organisms are occasionally pronounced, with identifiable inshore and offshore communities, structured in large part by gradients in predation. Although the structure of plankton communities is known to be perturbed by incursions induced by upwelling and downwelling, the reestablishment of community structure following relaxation of the wind is not well understood.

- Both our observational and modeling capabilities have reached the point where an intensive, interdisciplinary coastal processes dynamics study is both possible and necessary in order to elevate our quantitative understanding to the mesoscale level. To launch such a study, however, coordinated logistical/operational/intellectual assets need to be brought to bear both from the Great Lakes and from the oceanographic and remote sensing communities, e.g., larger vessel(s), aircraft/satellite mounted sensing systems, etc.

B. Guiding Questions

The General Question

The central focus of a CoOP Great Lakes process study is to address the following general question:

> **What is the influence of vertical stratification on the cross-margin transport of biological, chemical and geological materials in the coastal margins of the Great Lakes?**

Within this context, a number of important, process-directed issues evolved from the workshop deliberations. Interdisciplinary projects, part of a CoOP Great Lakes study, should address one or more of these specific processes.

1. Storm-Induced Transport Processes:

> **How important are the patterns and intensities of storms in the overall transport of biologically, geologically and chemically important materials and biota?**

From the earliest days of the IFYGL study, it was well known that horizontal, vertical and temporal gradients for most chemical, biological and physical properties in the nearshore zone are quite strong, especially during times of significant atmospheric heating or cooling. During conditions of spring heating a variety of processes transfer material from onshore to offshore including turbulent shear stress, eddies, currents, convection/advection and turbulent diffusion. These processes aggregate into higher order phenomena such as coastal jets, thermal bars and the thermocline, which have controlling effects on the net offshore flux of material. The energy and mass required to generate these processes are derived from several agents external to the nearshore zone, principally episodic storms, ice and ice-melt, and tributary input, all of which are probabilistic in their intensity, occurrence, and temporal behavior.

A variety of the studies recommended in this proposed research program concentrate on direct measurement and parameterization of these important transport processes. This series of questions is based upon the broad objective of determining whether the episodic character of the boundary loadings, from which transport processes derive, is an important determinant of the net cross shelf flux of biologically, geologically and chemically important material.

Ice-melt and the associated large tributary runoff occur in a relatively short period and form a once-per year system perturbation. In contrast, storms perturb the system chronically, coming every 5-8 days in fall, winter and spring and every 7-10 days in the summer. Thus, some scientists have asserted that the condition of the lake at the end of the ice season is the principal factor in regulating the subsequent annual offshore flux. Some speculate that the strongest wind event is the single best determinant, while others assert that the spring melt runoff event is the most crucial. As opposed to these "event dominance" theories of nearshore processes, the nearshore exposure to the chronic year-long pattern and intensities of storms is often suggested as a dominant correlate with the offshore flux. An examination of the validity of these assertions forms the basis of the scientific objectives of this research section.

Sub-Questions:

- Do wind events, tributary runoff, or initial conditions at ice-breakup dominate the resulting cross-shelf material distributions observed during the transition to full stratification in spring?
- In any one year, will a single large annual storm event dominate the resulting cross-margin transport, transformation and fate of biologically, geologically and chemically important materials or will the integrated contributions of all annual episodic storms be most important?
- Will the pattern and intensity of storm events result in the offshore transport during the spring transition of fundamentally different sediments and associated biological, geological and chemical materials?
- How does the pattern and intensity of episodes affect biological productivity and the transport of biota offshore during the spring transition?
- Will the pattern and intensity of nearshore recycling generated by wind driven circulation over whole lake basins affect the type and character of biological, geological and chemical materials and biota that are transported offshore during the spring transition?

2. Biological Transformations:

How are differences in the composition and productivity of the nearshore and offshore plankton communities maintained in an advective environment?

Existing evidence indicates that for all the Great Lakes except Erie, (which typically freezes over during winter), the isothermal mixing period is a time of energetic redistribution of materials and recharge of the water column with nutrients. Significant production occurs near the end of this period, when daylength increases sufficiently to support positive net photosynthesis in the water column. The spring bloom initiated during this period ends when nutrients are exhausted, especially following the onset of thermal stratification.

The inshore community varies tremendously among the lakes. Plankton communities established in inshore and offshore regions after the spring bloom are fundamentally different (see Working Group Report "Transformations of Solutes, Particles, and Organisms", Appendix 2.H.). Changes occur in the size structure of the primary producer community as large diatoms become scarce. In Lakes Michigan, Ontario and eastern Lake Erie, for example, the inshore community in the summer is dominated by small cladocerans, few calanoid copepods, large numbers of blue-green and green algae, and small flagellates. On the other hand, the offshore community is dominated by medium-large (ca. 1 mm) zooplankton, large numbers of calanoid copepods, low numbers of blue-greens and greens, but large numbers of flagellates. In inshore waters, phytoplankton biomass drops and dominance shifts to species with lower sinking rates than diatoms. In the zooplankton community dominance shifts from copepods to cladocera. The relative importance of *in situ* recycling, external inputs (rivers, rain, dryfall), vertical eddy diffusion, and lateral advective transport and mixing in maintaining this biological community are unknown. In offshore waters, biomass of epilimnion phytoplankton drops below inshore values, deep chlorophyll maxima appear, and larger-bodied zooplankton dominate. It is virtually certain that the offshore phytoplankton community depends principally on nutrients recycled *in situ*, which were originally made available during the previous isothermal mixing episode. Unknown, however, is the extent to which processes controlling offshore production depend upon episodic perturbations to the nutrient balance resulting from physically driven processes, such as upwelling and excursive gyres from a longshore current, vs. biological factors. Comparative studies between communities of alternative organization are a logical next step in Great Lakes plankton investigations. The existence of distinct inshore and offshore communities, derived from a common species pool and maintained despite cross-shelf mixing, argues for the existence of strong organizing forces.

The Great Lakes have two important predation gradients: fish planktivory, which decreases from inshore to offshore, and invertebrate planktivory which varies inversely to fish planktivory. The net result is an inshore zooplankton community dominated by small species that are less susceptible to predation by fish.

Although some large-bodied offshore zooplankton species can prey effectively on small inshore species, predation alone may not be the cause for cross-shelf compositional differences in zooplankton communities. Distinct inshore and offshore biological communities (algae, zooplankton and fish) exist during the stratified season, and despite the frequency of upwelling events, inshore communities reestablish themselves after each physical displacement and maintain a consistent structure. Differences in food availability or food quality may contribute to differences in the composition of inshore and offshore plankton communities. The role that variation in prey types and availability plays in zooplankton community structure is unknown and should be investigated by direct experimentation. Rates of nutrient cycling, trophic transfer efficiencies, and material fluxes are potentially different, as well, and deserve investigation.

The study should examine the causes and effects of disturbances to these biological gradients with particular attention to mechanisms by which they reestablish themselves in the water column. Sites should have gradients in biological community structure across regions that are disrupted episodically by upwelling or coastal jet features. In order to evaluate the relative importance of inflows, wet and dry precipitation, lateral exchange, vertical mixing, and *in situ* recycling, it would be desirable to contrast lakes with large differences in nutrient condition, such as Lake Erie versus Lakes Huron, Superior, or Michigan. A functional circulation model is currently available for Lake Erie, and comparable models are under development for Lakes Michigan and Ontario. These models may provide initial estimates of physical exchange rates, needing refinement by additional observations. New modeling efforts will be needed to combine the physical output with biological process rates.

Sub-Questions:

- What controls biological production and to what extent does sediment-water coupling during the isothermal period influence annual scale biological production processes for both inshore and offshore regions?
- Is cross-shelf transport of nutrients and productivity of minor importance during the stratified period, such that 90% or more of offshore biological activity is supported by local phenomena (thermal mixing, remineralization, etc.)?
- Are the impacts of land margin interactions during the stratified period confined to a relatively small volume of the lake with its associated biota?
- What is the importance of trophic interactions for biological production along the near-shore to offshore gradient?

3. Sediment-Water Interactions:

What is the episodic nature of the flux of biologically, geologically and chemically important materials between the sediment and water column?

Particle production and transport plays a major role in the behavior of nutrients and contaminants in the Great Lakes. Upon entering the lakes, compounds that are rapidly scavenged by particles are removed to the sediments within a few months or less. A large fraction of the particulate material and associated constituents are transported across the margin (in both directions) within a benthic nepheloid layer. After reaching the bottom, the settled materials are mixed by the activities of bottom-dwelling organisms and physical disturbance into a homogeneous pool representing years to decades of recent sedimentation.

Concern with the persistence of recently regulated and controlled trace contaminants and nutrients (e.g., PCB, lead, phosphorus), and an increasing interest in restoration have led to a closer examination of the processes involved in the exchange of these and other materials between the water column and the large inventory stored in the lakes' sediments. It is apparent from the relatively slow decline in the concentrations of particle-associated constituents in water and biota, despite large declines in external loads, that sediments are a leaky sink; small concentrations persist in the water for decades owing to processes that remobilize materials from the bottom.

Even though the Laurentian Great Lakes are deep, resuspension of sediment is very important in cycling compounds with a high affinity for particulate matter. Annually, during the unstratified period, resuspension and sedimentation of particulate matter from the sediments scavenge newly introduced constituents, but also re-expose lake waters to those materials stored in the resuspendible pool of surface sediments.

Bioturbation and resuspension maintain sediment-associated constituents in intimate contact with the overlying water. Consideration of seasonal timing is also important in attempting to assess the overall importance of these processes. Significant phytoplankton production occurs prior to lake stratification. Remineralization coupled with resuspension sets the initial nutrient conditions for lake waters in the spring. Nutrient utilization via primary productivity prior to stratification is a major factor in determining the size of the pool of recyclable epilimnetic nutrients once stratification begins.

Sub-Questions:

- What are the relative fluxes of various biologically, geologically and chemically important materials from particle resuspension, pore fluid resuspension, diffusion, biogenic mixing and irrigation, and benthic food web activity?
- How important are various episodic events in these fluxes?
- How is the benthic nepheloid layer created and maintained, and how do transport rates associated with this layer compare to the overall water column?
- What time and energy scales are involved in the post-depositional remobilization and transport of sediments into depositional zones?

4. Thermal Structure:

How and to what extent are cross-barrier fluxes and biological productivity affected by the strength of the thermocline and thermal bar?

The principal sources of momentum and kinetic energy to the water column are wind stress acting directly on surface currents, and the wind stress giving rise to surface waves that, in breaking, release their momentum and energy to the water column. Terray et al. (1995) demonstrated that considerably more energy is delivered to the water column through these agencies than previously estimated. Consequently, the primary mixing process is vertical from the top down. Secondary mixing occurs via gradients in the current regime, both horizontally and across the thermocline, and through the interaction of hypolimnetic currents with the bottom. Vertical mixing is inhibited by the development of the thermocline, and the consequences of wave-induced mixing on thermocline development remain to be explored.

A thermal bar, on the other hand, which separates the well-mixed interior of the lake from the strongly stratified coastal region, restricts horizontal mixing by deflecting water approaching the bar downward. Convergence at the thermal bar occurs when temperatures on either side of the bar straddle the temperature of maximum density (approximately 4° C for freshwater). Mixed waters at the bar, being maximally dense, sink to the bottom or until they encounter water of similar density. This phenomenon does not occur in the oceans, where the effects of salinity keep the density-temperature curve monotonic in the range above freezing. The effect of a convergence zone at a thermal bar is two-fold: 1) the bar remains distinct until the water masses on both sides of the bar are warmer (or colder) than the temperature of maximum density; and 2) water, carrying biologically, geologically and chemically important materials, sinks efficiently to the bottom in the vicinity of the bar.

During stratified periods, currents generated by coastal upwelling/downwelling events are important in the vertical and horizontal redistribution of nutrients and biota and in the transport of materials across the coastal margin. Particularly worthy of further investigation is what happens after the downwelling-producing forces are relaxed. Only partially explored, as one of the central themes of coastal dynamics, is the process of geostrophic readjustment, disclosed by the offshore-directed propagation of thermal fronts from the downwelled region.

Sub-Questions:

- What is the dependence of cross-margin fluxes of momentum, energy and biologically, geologically and chemically important materials on the strength of the thermocline?
- How does the thickness and transparency of the epilimnion and the strength of the thermocline affect exchange with the atmosphere of momentum, energy and mass?
- What are the energy and momentum fluxes that deepen the thermocline, drive upwelling and downwelling events, and transport materials normal to the shore?
- What biophysical feedbacks influence the development of the thermocline?

- What is the dependence of primary productivity on the strength of the thermocline?
- What is the effect of turbulence on the biological productivity in the epilimnion?
- What processes control the effectiveness of the thermal bar in isolating biological communities, and in transporting material vertically in the convergence zone?

5. Jets, Meanders and Eddies:

What is the role of eddy transports related to the coastal jet in the cross-margin flux of suspended and dissolved materials?

Concentrated boundary currents, their meanders and daughter eddies play a key role in the cross-margin transport of material on large water bodies (Robinson, 1983). Boundary currents, and to a lesser extent, eddies, have also been documented and described theoretically in the Great Lakes (Csanady, 1968, 1972; Scott et al., 1971; Csanady and Scott, 1974; Simons et al., 1985; Boyce et al., 1989), and are, of course, well documented in the oceans.

The much smaller scale of lakes leads to a different balance of forces in determining the current structure. Boundary currents arise in response to wind stress and the resulting Coriolis-induced Ekman drift. In the Great Lakes the prevailing westerly winds produce a southeastward Ekman transport which leads to intensified southern boundary currents. The intensity of the current falls off with distance from the coast with a scale related to the internal radius of deformation (Csanady and Scott, 1974). These "coastal jets", like the western boundary currents of the ocean, produce meanders and sometimes spawn eddies or "rings", which may be responsible for significant transport normal to the coast. The pattern of mercury and mirex deposition in the sediments of Lake Ontario (Thomas, 1972, 1983) reflects the transport of the coastal jet along the south shore of Lake Ontario from the source in the Niagara River. Significant deposition in the center of the lake suggests important cross-margin transport, possibly due to meanders and eddies.

It has been shown in Lake Michigan that there is a sharp contrast between nearshore current regimes in winter and summer. During unstratified conditions in winter, the nearshore currents are predominantly shore-parallel and directly wind responsive within about 10 km of shore (Sato and Mortimer, 1975). But, during stratification in summer and fall, the currents at 9 km from shore are dominated by inertial "waltzing", not tied to wind speed and direction. This fundamental seasonal contrast profoundly affects the mode and effectiveness of dispersal. Winter coastal jets, if such exist, will be directly wind-responsive and barotropic, while summer coastal jets will be baroclinic and will be associated with shore-trapped Kelvin-like waves, achieving maximum current velocity some distance offshore. Coastal dispersal and plume dynamics have been subject to some controversy

(Mortimer, 1981). Both long, narrow, coherent shore-hugging jets with little dispersal and turbulent eddy plumes with a wide spectrum of eddy sizes and far field dispersion have been proposed. Dilution is clearly greater in the latter and the general question of near-field and far-field plume dispersal merits further clarification.

It seems likely that meanders and eddies associated with coastal jets play a significant role in the cross-margin transport of biologically-important material. However, the observational studies conducted so far are not sufficient to provide reliable estimates of the efficacy of this mechanism.

Sub-Questions:

- What governs the jet instability that leads to the formation of meanders and eddies?
- What is the frequency of occurrence of offshore transport associated with meanders and eddies?
- What is the magnitude of the offshore transport of dissolved and suspended biologically, geologically and chemically important materials associated with meanders and eddies?

C. Plan for Action

1. Introduction : CoOP Philosophy

The CoOP approach is to quantify key processes in a few areas well enough to model them effectively in a variety of regions. A CoOP study in the Great Lakes should further the science of these water bodies as well as elucidate fundamental processes common to all coastal regions.

2. Setting

Within the Great Lakes, many of the processes which dominate cross-margin transport are heavily influenced by the underlying annual transitions from isothermal winter conditions to summer vertically stratified conditions and back to isothermal conditions again in the fall. Because of the importance of the winter-summer transition for biological production as well as physical transport, this period was the focus of a number of suggested studies. It represents a time when the biological signal changes dramatically in concert with fundamental changes in the physical dynamics of the lakes. The isothermal period, usually beginning in late fall, and continuing through early summer, is the most dynamic period of onshore-offshore fluxes. The spring transition to stratification may set upper limits on biological production in some of the lakes (e.g., southern Lake Michigan) and the period contains a large range in scales of temporal forcing, short and long term, chronic as well as episodic. The onset of stratification is initiated by the formation of the thermal bar which has a striking impact on onshore-offshore transport. This is also a period which is data-poor, largely because of the difficulty of working under the harsh winter conditions (subfreezing temperatures and high winds) typical of the Great Lakes. The presence of ice on all or part of the lake is an important aspect of the hydrodynamics of the lakes during the winter, whether solid, partial or broken ice cover.

A focus on this transitional period, however, is not intended to exclude other parts of the limnological year from study. Indeed, to compare the magnitude of effects, observations throughout the year are necessary. The data base for the transitional periods is weak, however, and an appropriate priority should be given in planning field studies to observations collected during these periods.

3. Location of Field Program

No clear consensus was reached by the workshop with respect to an ideal location for a CoOP study. Much of this arises from the fact that the Great Lakes are very diverse in morphometry and ecology, varying from the deep (>400 meters) oligotrophic Lake Superior, to the shallow (mean depth 17 meters), eutrophic Lake Erie.

TABLE 1. Great Lakes Physical Features

Feature	Unit	Superior	Michigan	Huron	Erie	Ontario
Elevation	m	183	176	176	173	74
Drainage Basins	km^2	127,700	118,000	134,000	78,000	64,030
Lake Surface	km^2	82,100	57,800	59,600	25,700	18,960
Average Depths	m	147	85	59	19	86
Maximum Depths	m	405	281	229	64	244
Retention Time	yrs	191	99	22	2.6	6
Shoreline Length	km	4,385	2,633	6,157	1,402	1,146

Some processes are best studied in one system vs. another. Some consistent themes did emerge, however.

- Previous studies, databases and models for some of the lakes (particularly Michigan, Erie and Ontario) are much more extensive than others. Such background information is extremely useful in developing and formulating new directions and approaches. On the other hand, Lakes Superior and Huron have been less well studied and, certainly, deserve attention. The major trade off is that the development and application of physical models is much further advanced in Lakes Michigan, Erie and Ontario. The International Field Year for the Great Lakes - Lake Ontario, findings should be revisited and reviewed in depth, particularly the nearshore observations.

- Although there is currently no counterpart to CoOP in Canada, the potential benefits derived from a joint Canadian - U.S. study were unanimously recognized. Consequently, studies which furthered this potential by proposing significant work on one of the international lakes (i.e., all but Michigan) were favored. Comparative studies on Michigan would not be excluded and many working groups suggested Lake Michigan studies for a variety of reasons, from an extensive research database on the lake to its physical dynamics.
- Comparative studies (both intra- and inter-lake) were often suggested as valuable for contrasting forcing functions and variables such as basin morphometry (depth, turnover time, slope), orientation to the prevailing wind field, fluvial inputs, and trophic status.

4. Duration

Interannual variability is a difficult variable to eliminate in any study. It is not the intention of a CoOP study to look at seasonality *per se*, nor long term phenomena. However, with the pronounced seasonality and variability of the lakes from year to year, a minimum of two, and ideally three field seasons, is proposed. With the additional complexity generated by a multi-investigator, interdisciplinary study, a minimum five year program will be needed to accomplish the goals of a CoOP effort on the Great Lakes. An approximate time frame for such a study would be:

Yr 1. Pilot Effort: planning and investigator interaction, existing data synthesis, initial modeling effort, pilot studies and testing, development of tiered sampling strategies;

Yr 2-3. Field Studies: process investigations, fine tuning of nested sampling schemes, interlake comparative studies;

Yr 4-5, Synthesis: synthesis is used here in the sense of being beyond the manuscripts that individuals or small groups will publish as primarily disciplinary efforts. An iterative process that synthesizes models, process studies and data should be established early in the study and should culminate with major synthesis efforts in the final years, during which there should be no field work. Synthesis of interdisciplinary studies requires a major effort and often does not receive sufficient standing in the overall planning.

5. Modeling

While every proposed study of Great Lakes processes will benefit from a coordinated modeling study, those dealing with fluxes of material near the boundaries will depend rather substantially upon models. The objective of this overall study is to determine the cross-shelf transport of chemical, particulate and biological constituents; this includes both time-varying and mean fluxes. The ability to measure currents for extended periods of time at a few points in the water column and at horizontally isolated moorings is quite good. However, the ability to make similar measurements of chemical or biological constituents is less well developed. Modeling will provide a means to hridge the data gaps. Coupling physical models with biological, geological and chemical processes and focusing on the nearshore will be the fundamental challenge.

Three types of models, process, simulation and assimilation, would be useful for this study. Process models idealize some aspect of the problem. Typically, the forcing, ecology and geometry are simplified. The advantage of such models is that they are relatively easy to implement and analyze. Of particular interest is the ability of these models to explore hypotheses for the existence of specific phenomena.

Simulation models would attempt to reproduce the circulation, thermal structure and resultant constituent fields and their transport when appropriately forced. These models should contain all of the essential physics and ecology (as identified from data and process models), have realistic topography, and be forced by realistic surface and boundary fluxes.

Assimilation models may be used to synthesize and interpolate appropriate data sets. In oceanographic situations, these models have proven to be valuable tools for interpolating between measurements both in time and space. The physics of these models need not be complete, because the data are used to control the evolution through space and time. The better the physics of the model, the less data are required to maintain a satisfactory field estimate. One reasonable scenario is that a data assimilation model could be used to describe the large-scale structure of the lake circulation in order to set the context for the local dynamics experiments.

Development of coupled chemical-biological-particulate-physical models is a priority for a Great Lakes CoOP study. Among the modeling efforts targeted for inclusion are the following:

1. Expansion of the Great Lakes Forecasting System (Schwab & Bedford, 1994) to include biologically, geologically and chemically important materials.
2. Improvement and expansion of hydrodynamic and mass transport models to include: wave-current interactions; tributary coupling with nearshore circulation; thermal bar and thermal front formation and propagation; upwelling/downwelling; coastal plume/jet propagation

and dispersion; air-water exchange; and grid refinement for resolution of fronts and interfaces.

3. Development of a spatially-dependent sediment transport model containing benthic-pelagic coupling under mean and episodic storm conditions, chemical exchange between the sediments and overlying water, net depositional losses and particle history.

4. Development and incorporation of productivity, trophic interaction and food chain models.

An important aspect of any proposed study is the inclusion of a significant modeling effort "upfront", and considerable emphasis should be given to modeling and data synthesis activities. There is a clear requirement for the interaction and feedback between the modeling and the observational phases of the study.

6. Observations

Because the lakes are closed systems, smaller scale studies of local dynamics may be integrated into larger scale studies of the whole basin in a manner and with a coherence that may not be easily duplicated in other, more open coastal systems. One of the interesting and important differences in the hydrodynamics of the Great Lakes vs. that of the coastal ocean lies in the recirculating nature of the Great Lakes flow field. Because these systems are bounded, cross-margin transport, instead of resulting in long-term loss of material offshore, as in the case of the open ocean, often results in the return of material to the nearshore zone over periods as short as a few days. Consequently, two scales of observations are valuable: a local dynamics experiment on a scale of km's to 10's of km, and a study to include sampling on a scale sufficient to resolve basin scale processes such as propagating waves and wind-driven circulation. Conservation of mass within a basin dictates closure, a refining requirement for models and mass balance calculations not generally available in open systems. This facet of a Great Lakes study should be maximized to the degree feasible within the constraints of time and resources.

This argues for measurements (and models) on scales sufficient to resolve basin scale processes, as well as measurements (and models) sufficiently detailed to resolve onshore-offshore fluxes on the scale of kilometers or less. One approach is to develop a nested or tiered sampling scheme which sets the spacing and frequency of observation based upon the process scale. Timing the location and spacing of moorings, stations, transects and field measurements will need to be determined initially in conjunction with process models and existing meteorological and limnological data. The observational program should accomplish two objectives: 1) monitor the distribution of key variables (meteorological, biological, chemical, geological and physical) in three dimensions, and 2) measure and parameterize the rates that govern changes in the key variables (e.g., grazing rates, plankton growth rates, sedimentation, air-water fluxes), both at a temporal and spatial resolution sufficient to answer the questions posed by this study.

Observations are relevant and necessary at three general levels: basin-wide synoptic data (largely remotely sensed observations), stationary observational platforms and mooring arrays for acquiring time series data sets of critical parameters, and shipboard surveys. The exact mix of observational modes utilized will depend upon the nature of the final study undertaken and is left to the investigators involved.

Remote sensing of surface properties (temperature, velocity fields, surface structure) are powerful tools for observations over length scales from a few pixel lengths (one pixel = 1.3 to 2.5 km for AVHRR data), to lengths approaching that of the basin. Full attention should be paid to the synoptic imaging capabilities of satellite and aircraft mounted sensors and to the search for water-mass labels, both optical and chemical, and both natural (isotopes, isotope ratios, specific conservative tracers, sediment resuspended by storms) and artificial (dyes, current following drogues, point source effluents). Some remote sensing instruments are relatively well developed and can provide resolution in time and space unavailable by any other means. AVHRR temperature data, for example, are especially valuable in the Great Lakes with twice daily images with a 1 km horizontal resolution. The visible spectrum has also proven highly useful in observing basin-wide events (e.g., $CaCO_3$ precipitation events or "whiteings") and the physical features (eddies, etc.) they reveal. Further attention should be given to recent advances in high frequency radar surface current measurements, such as OSCAR or CODAR.

The limitation of both of these types of "remotely-sensed" observations is the lack of vertical resolution. This can be ameliorated, however, when co-located, ground-truthed and coincident with moorings and shipboard surveys.

An array of moorings can provide the long time series measurements needed to determine mean circulation and eddy fluxes of heat, mass, chemical and biological constituents. Measuring devices could include: meteorological instruments, current meters, thermistor strings, acoustics, optical properties (transparency, fluorometry, turbidity), sediment traps, particulate pumps, etc. Their principle drawback is the lack of spatial resolution, but they are critical for evaluating episodic events, the frequency and duration of mass fluxes, and the vertical expression of surface phenomena. A moored array should be in place for the duration of the field effort. Because of winter icing, surface buoy deployments may need to be reconfigured. Objectives for a multiuse, fixed site array could include:

- to resolve onshore-offshore flow in response to wind driven episodes on scales equivalent to a local dynamics experiment
- to monitor, in 3 dimensions, the transition from the isothermal state to the development of the thermal bar and the onset of stratification
- to provide estimates of the exchange of heat, momentum, and mass across the air-water interface
- to provide sufficient detail to estimate horizontal fluxes (both alongshore and shore-normal) for biologically, geologically and chemically important materials and to provide the means for making empirical measurements of sediment and particulate fluxes from the nearshore to net depositional regions with particular attention to bottom boundary layer flow and the spin-up and decay of the nepheloid layer
- to provide estimates of transport mechanisms driving the vertical upward flux of materials from the sediments to the overlying water and the depositional flux of materials from the water column to the sediments
- to monitor key parameters diagnostic of a biological response to physical events

With the advent of acoustic modems, cellular phone lines, etc. some nearshore monitoring may be accomplished by direct link-up with shore-based stations for real time data collection/analysis and for triggering of event-driven sampling. Large experimental platforms have been used in Canada, e.g., in Lake Ontario, which provide *in situ* laboratory space, electrical power, etc. NOAA and Environment Canada meteorological buoys (wind speed and direction, temperature, wave height) are maintained in the central part of the lakes during the navigational season with continuous data via phone line.

Waterworks intakes (for drinking and cooling water) around the Great Lakes offer potential as "continuous monitoring posts" and as sources of archived data. Many intakes pump and record continuously, including during winter and from near-thermocline depth in summer. Temperature, therefore, is an indicator of upwelling/downwelling and internal wave activity; and such intakes are also sources of routine water quality data and can be sampled for other special purposes.

Sea-going observations aboard ships could involve at least two types of surveys, intended both to extrapolate/interpolate fixed array data objectives and to provide additional laboratories and sampling capabilities. Smaller vessels, routinely available in the Great Lakes, would be advantageous for conducting underway measurements via Acoustic Doppler Current (ADC) profilers, side-scan bottom profilers, flow through analytical set-ups and towed instruments, like SeaSoar. These vessels are typically shallow draft and could operate nearshore with few restrictions beyond sea state. Because their ability to stay on station is limited, however, at least one larger vessel would need to be committed to many of the traditional sampling techniques (hydrocasts, net tows, box coring) and for any experimental work requiring significant laboratory space, berthing or prolonged 24 hr operations. Specialized instrumentation (ROVs, benthic landers, etc.) may also aid in observational studies difficult to accomplish from the surface. Lagrangian measurements via instrumented near surface drifters deployed from ships are also powerful tools for studying cross-margin transport in a local dynamics experiment, particularly when combined with remote sensing data, instrument arrays and ship surveys. At least 4 cruises per year are anticipated.

7. Facilities

The facilities required to carry out these observations exist in some form within the combined oceanographic/Great Lakes community. Coordinating their use will be a major task. Aside from the EPA vessel, the R/V Lake Guardian, there is no large research vessel in the lakes which can accommodate a large team (>20) of interdisciplinary scientists. It may be necessary to commit one or more of the larger UNOLS vessels, currently involved in coastal ocean science, to the Great Lakes during periods of intensive shipboard studies. Smaller vessels (<90' LOA) capable of day or week operations are available within the Great Lakes. Winter operations may require vessels capahle of operating in ice up to 0.5 meter thick. Since locks on the seaway are closed in the winter, ships will need to be pre-positioned for cross-margin studies, and remain until ice break-up.

8. Cooperation with Other Programs

The workshop stressed the need for cooperation with other programs and particularly with Canadian researchers. In addition to these scientists, the Canada Centre for Inland Waters (CCIW) has a well equipped research fleet and other unique resources (buoys, moored platforms, etc.) that would significantly enhance a binational effort. NOAA's Great Lakes Environmental Research Laboratory, with locations in Ann Arbor and Muskegon, Michigan, is currently the largest laboratory dedicated to Great Lakes science and has the only major physical oceanographic capability in the Great Lakes on the U.S. side. The NOAA Coastal Ocean Program sponsored a workshop in December 1992 to initiate a major effort in the Great Lakes. The timing for a comhined CoOP-NOAA COP effort would appear to be excellent. The U.S. Environmental Protection Agency operates the only large U.S. research vessel in the lakes, and is charged with regulatory and monitoring responsibilities.

CoOP has evolved in a sequential fashion with studies occurring largely in series. In order to build upon previous and ongoing CoOP efforts (e.g., Duck, NC-Nearshore Dynamics Study; Air/

Sea Interaction Study; the proposed Wind-Driven Shelf Study; and the proposed Great Lakes Study) interactions among CoOP investigators in these efforts should be planned.

D. Conclusion

Closed basins, like the Great Lakes, offer substantial and unique advantages in addressing coastal ocean process questions. They are amenable to observational campaigns and to modeling. They avoid some of the difficulties and ambiguities of open boundaries. The Great Lakes display, not only basic, well-developed coastal processes, but also distinct seasonally-dependent differentiation between inshore processes and offshore mesoscale and whole basin phenomena. This differentiation is based in large part upon the annual transition from isothermal to stratified conditions, a period which has received little attention relative to its importance in the lakes' dynamics. This emerged, therefore, as a focus for a new research initiative which will advance the state of coastal ocean science by addressing fundamental science questions.

The Great Lakes also currently face all the major coastal ecosystem environmental issues identified in the National Research Council report on *Priorities for Coastal Ecosystem Science* (NRC, 1994), namely: eutrophication, habitat modification, hydrologic and hydrodynamic disruption, resource exploitation, toxic effects, nonindigenous species introduction, climate change and variability, shoreline erosion and hazardous storms, and pathogens and toxins affecting human health. Many of these issues are heightened in importance in the Great Lakes by virtue of the fact that drinking water for a substantial fraction of the population of North America is drawn directly from the nearshore zone. Thus, in terms of societal impact, the Great Lakes, like coastal regions everywhere, play an extremely important role in regional and national environmental and economic health.

Within this dual context of 1) the importance of coastal processes in structuring the system and 2) the socioeconomic importance of the resource and our ability to effectively manage it, a process study with the unique focus of the CoOP approach is deemed both timely and valuable for coastal science and the policy decisions it supports. It was clear from the workshop deliberations, that the coupling mechanisms linking the nearshore and offshore are not well understood in the Great Lakes, and that a large scale, interdisciplinary effort employing advanced techniques for modeling and observation is the only way in which critical gaps in our understanding of Great Lakes cross-margin transport processes will be closed. This report highlights that need and the widespread interest in a coastal ocean process study in the Great Lakes.

References (including Appendices)

Achman, D.R., K.C. Hornbuckle and S.J. Eisenreich, 1993. Volatilization of PCBs from Green Bay, Lake Michigan. *Environmental Science and Technology*, **27**, 75-87.

Agrawal, Y., E.A. Terray, M.A. Donelan, P.A. Hwang, A.J. Williams III, W.M. Drennan, K.K. Kahma and S.A. Kitaigorodskii, 1992. Enhanced dissipation of kinetic energy beneath surface waves. *Nature*, **359**, 219-220.

Assel, R., F. Quinn and G. Leskevich, 1983. *Great Lakes ice atlas*. NOAA-GLERL, Ann Arbor, Michigan.

Atlas, E. and C.S. Giam, 1986. Sea-air exchange of high molecular weight synthetic organic compounds. In: *The Role of Air-Sea Exchange in Geochemical Cycling*. P. Buet-Menard (Ed.), D. Reidel Publishers, Dordrecht, p. 295-323.

Baker, J.E. and S.J. Eisenreich, 1989. PCBs and PAHs as tracers of particulate dynamics in large lakes. *Journal of Great Lakes Research*, **15**, 84-103.

Bartell, S.M., J.E. Breck, R.H. Gardner and A.L. Brenkert, 1986. Individual parameter perturbation and error analysis of fish bioenergetics models. *Canadian Journal of Fisheries and Aquatic Sciences*, **43**, 160-168.

Barth, J.A., 1994. Short-wavelength instabilities on coastal jets and fronts. *Journal of Geophysical Research* **99**(C8), 16095-16115.

Bedford, K. and M. Abelrhman, 1987. Analytical and experimental studies of the benthic boundary layer and their applicability to near bottom transport in Lake Erie. *Journal of Great Lakes Research*, **13**(4), 628-648.

Blanton, J.O., 1974. Nearshore lake currents measured during downwelling and downwelling of the thermocline in Lake Ontario. *Journal of Physical Oceanography*, **4**, 415-424.

Boyce, F.M., 1974. Some aspects of Great Lakes physics of importance to biological and chemical processes. *Journal of Fish Research Board of Canada*, **31**, 689-730.

Boyce, F.M., M.A. Donelan, P.F. Hamblin, C.R. Murthy and T.J. Simons, 1989. Thermal structure and circulation in the Great Lakes. *Atmosphere-Ocean*, **27**(4), 607-642.

Boynton, W.R. and W.M. Kemp, 1985. Nutrient regeneration and oxygen consumption by sediments along an estuarine salinity gradient. *Marine Ecology Progress Series*, **23**, 45-55.

Brandt, S.B., 1986. Food of trout and salmon in Lake Ontario. *Journal of Great Lakes Research*, **12**, 200-205.

Brandt, S.B. and J. Kirsch, 1993. Spatially-explicit models of striped bass growth in the mid-Chesapeake Bay. *Transactions of the American Fisheries Society*, **122**, 845-869.

Brandt, S.B., J.J. Magnuson and L.B. Crowder, 1980. Thermal habitat partitioning by fishes in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences*, **37**, 1557-1564.

Brandt, S.B., D.M. Mason and E.V. Patrick, 1992. Spatially-explicit models of fish growth rate. *Fisheries*, **17(2)**, 23-35.

Brandt, S.B., D.M. Mason, E.V. Patrick, R.L. Argyle, L. Wells, P. Unger and D.J. Stewart, 1991. Acoustic measures of the abundance and size of pelagic planktivores in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences*, **48**(5), 15 pp.

Brink, K.H., J.M. Bane, T.M. Church, C.W. Fairall, G.L. Geernaert, D.E. Hammond, S.M. Henrichs, C.S. Martens, C.A. Nittrouer, D.P. Rogers, M.R. Roman, J.D. Roughgarden, R.L. Smith, L.D. Wright, J.A. Yoder, 1992. *Coastal Ocean Processes: A Science Prospectus*. WHOI Technical Report 92-18, Woods Hole Oceanographic Institution, Woods Hole, MA.

Brooks, A.S. and D.N. Edgington, 1994. Biogeochemical control of phosphorus cycling and primary production in Lake Michigan. *Limnology and Oceanography*, **39**, 961-968.

Bunt, C.M., H.J. MacIsaac and W.G. Sprules, 1993. Pumping rates and projected filtering impacts of juvenile zebra mussels, *Dreissena polymorpha*, in Western Lake Erie. *Canadian Journal of Fisheries and Aquatic Sciences*, **50**, 1017-1022.

Cedarwall, H., 1977. Annual macrofauna production of a soft bottom in the northern Baltic proper. In: *Biology of Benthic Organisms*. B.F. Keenen, P. Oceidigh and P.J.S. Boaden (Eds.), Pergamon Press Ltd., Oxford, England, p. 155-184.

Chambers, R.L. and B.J. Eadie, 1981. Nepheloid and suspended particulate matter in southeastern Lake Michigan. *Sedimentology*, **28**, 439-477.

Cole, J.J., N.F. Caraco, G.W. Kling and T.K. Kratz, 1994. Carbon dioxide supersaturation in the surface waters of lakes. *Science*, **265**, 1568-1570.

Conley, D.J., M.A. Quigley and C.L. Schelske, 1988. Silica and phosphorus flux from sediments: importance of internal recycling in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences*, **45**, 1030-1035.

Cotner Jr., J.B. and R.G. Wetzel, 1991. 5'-Nucleotidase activity in a eutrophic lake and an oligotrophic lake. *Applied and Environmental Microbiology*, **57**, 1306-1312.

Cotner, J.B., W.S. Gardner, J.R. Johnson, R.H. Sada, J.F. Cavaletto and R.T. Heath, 1995. Effects of zebra mussels (*Dreissena polymorpha*) on bacterioplankton: Evidence for both size-selective consumption and growth stimulation. *Journal of Great Lakes Research*, **21**, 517-528.

Csanady, G.T., 1968. Motions in a model great lake due to a suddenly imposed wind. *Journal of Geophysical Research*, **73**, 6435-6447.

Csanady, G.T., 1972. The coastal boundary layer in Lake Ontario: Part. I, The spring regime. *Journal of Physical Oceanography*, **2**, 41-53; Part. II, The summer-fall regime. *Journal of Physical Oceanography*, **2**, 168-172.

Csanady, G.T., 1975. Hydrodynamics of large lakes. *Annual Review of Fluid Mechanics*, **7**, 357-386.

Csanady, G.T. and J.T. Scott, 1974. Baroclinic coastal jets in Lake Ontario during IFYGL. *Journal of Physical Oceanography*, **4**, 524-541.

DeAngelis, D.L., 1992. *Dynamics of Nutrient Cycling and Food Webs*. Chapman and Hall, New York, NY, 270 pp.

Donelan, M.A., 1990. Air-Sea Interaction. In: *The Sea: Volume 9: Ocean Engineering Science*. B. LeMehaute and D.M. Hanes (Eds.), Wiley Interscience, pp. 239-292.

Eadie, B.J., R.L. Chambers, W.S. Gardner and G.L. Bell, 1984. Sediment trap studies in Lake Michigan: resuspension and chemical fluxes in the southern basin. *Journal of Great Lakes Research*, **10**, 307-321 and Figure 12, p. 317.

Edgington, D.N., 1994. The effects of sediment mixing on the long-term behavior of pollutants in lakes. In: *Transport and Transformation of Contaminants Near the Sediment-Water Interface*. J.V. DePinto, W. Lick and J.F. Paul (Eds.), Lewis Publishers, Ann Arbor, MI, p. 307-328.

Edgington, D.N. and J.A. Robbins, 1990. Focusing time scales in Lake Michigan as revealed by fallout C2-137. In: *Large Lakes: Ecological Structure and Function*. M. Tilzer and C. Serruya (Eds.), Springer Verlag, New York, NY, p. 210-223.

Eisenreich, S.J. and K.C. Hornbuckle, 1995. Air-water exchange of semi-volatile organic chemicals in the Great Lakes. In: *Atmospheric Deposition of Contaminants to the Great Lakes and Coastal Water*. J.E. Baker (Ed.), Society for Environmental Toxicology and Chemistry.

Evans, M.S., 1990. Large lake responses to declines in the abundance of major fish predator: the Lake Michigan example. *Canadian Journal of Fisheries and Aquatic Sciences*, **47**, 1738-1754.

Evans, M.S. and D.J. Jude, 1986. Recent shifts in Daphnia community structure in southeastern Lake Michigan: A comparison of the inshore and offshore regions. *Limnology and Oceanography*, **31**, 56-67.

Fahnenstiel, G.L., G.A. Lang, T.F. Nalepa and T. Johengen, 1995. Phytoplankton productivity in Saginaw Bay, Lake Huron: Effects of zebra mussels (*Dreissena polymorpha*) colonization. *Journal of Great Lakes Research*, **21**, 465-475.

Fanning, K.A., K.L. Carder and P.R. Betzer, 1982. Sediment resuspension by coastal waters: a potential mechanism for nutrient recycling on the ocean's margins. *Deep-Sea Research*, **29**, 953-965.

Federal Reserve Bank of Chicago, 1991. *The Great Lakes Economy*. Federal Reserve Board and Great Lakes Commission, 163 pp.

Fee, E.J., R.E. Hecky, G.W. Regehr, L.L. Hendzel and P. Wilkinson, 1994. Effects of lake-size on nutrient availability in the mixed-layer during summer stratification. *Canadian Journal of Fisheries and Aquatic Sciences*, **51**, 2756-2768.

Fitzgerald, S.A. and W.S. Gardner, 1993. An algal carbon budget for pelagic/benthic coupling in Lake Michigan. *Limnology and Oceanography*, **38**, 547-560.

Floderus, S. and L. Hakanson, 1989. Resuspension, ephemeral mud blankets and nitrogen cycling in Laholmsbukten, South East Kattegat. *Hydrobiologia*, **176/177**, 61-75.

Folger, D.W., S.M. Coleman and P.W. Barnes, 1994. Overview of the southern Lake Michigan coastal erosion study. *Journal of Great Lakes Research*, **20**, 2-8.

Gardner, W.S., B.J. Eadie, J.F. Chandler, C.C. Parrish and J.M. Malczyk, 1989. Mass flux and "nutritional composition" of settling epilimnetic particles in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences*, **46**, 1118-1124.

Gardner, W.S., P.F. Landrum and J.F. Cavaletto, 1990. Lipid-partitioning and disposition of benzo[a]pyrene and hexachlorobiphenyl in Lake Michigan, *Pontoporeia hoyi* and *Mysis relicta*. *Environmental Toxicology and Chemistry*, **9**, 1269-1278.

Gardner, W.S., M.A. Quigley, G.L. Fahnenstiel, D. Scavia and W.A. Frez, 1990. *Pontoporeia hoyi*-A direct trophic link between spring diatoms and fish in Lake Michigan. In: *Large Lakes, Ecological Structure and Function*. M.M. Tilzer and C. Serruya (Eds.), Brock/Springer Series in Contemporary Bioscience, Springer-Verlag, Berlin, Germany, p. 632-644.

Glass, L. and M.C. Mackey, 1988. *From Clocks to Chaos: The Rhythms of Life*. Princeton University Press, 248 pp.

Goyke, A. and S.B. Brandt, 1993. Spatial models of salmonid growth rates in Lake Ontario. *Transactions of the American Fisheries Society*, **122**, 870-883.

Griffiths, R.W., 1993. Effects of zebra mussels (*Dreissena polymorpha*) on benthic fauna of Lake St. Clair. In: *Zebra Mussels: Biology, Impacts, and Control*. T.F. Nalepa and D.W. Schloesser (Eds.), Lewis Publishers, Chelsea, MD, p. 415-437.

Griffiths, R.W., W.P. Kovalak and D.W. Schloesser, 1989. The zebra mussel, *Dreissena polymorpha*, (Pallas 1771), in North America: impacts on raw water users. In: *Service Water System Problems Affecting Safety Related Equipment*. Electric Power Institute Symposium, Palo Alto, CA.

Halfman, B.M. and T.C. Johnson, 1989. Surface and benthic nepheloid layers in the western arm of Lake Superior, 1983. *Journal of Great Lakes Research*, **15**, 15-25.

Hartig, J., J.F. Kitchell, D. Scavia and S.B. Brandt, 1991. Interaction of food-web and nutrient effects in Lake Michigan and Lake Ontario. *Canadian Journal of Fisheries and Aquatic Sciences*, **48**(8), 1574-1580.

Hawley, N. and B.M. Lesht, 1995. Does local resuspension maintain the benthic nepheloid layer in southeastern lake Michigan? *Journal of Sedimentary Research*, **65**(1), 69.

Hebert, P.D.N., B.W. Muncaster and G.L. Mackie, 1989. Ecological and genetic studies on *Dreissena polymorpha* (Pallas): a new mollusc in the Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, **46**, 1587-1591.

Holdren Jr., G.C. and D.E. Armstrong, 1980. Factors affecting phosphorus release from intact lake sediment cores. *Environmental Science and Technology*, **14**, 79-87.

Hopkinson Jr., C.S., 1985. Shallow-water benthic and pelagic metabolism: evidence of heterotrophy in the nearshore Georgia Bight. *Marine Biology*, **87**, 19-32.

Hopkinson, Jr., C.S. and R.L. Wetzel, 1982. *In situ* measurements of nutrient and oxygen fluxes in a coastal marine benthic community. *Marine Ecology Progress Series*, **10**, 29-35.

Irbe, J.G. and R.J. Mills, 1976. *Aerial surveys of Lake Ontario water temperature and description of regional weather conditions during IFYGL - January 1972 to March 1973*. Environment Canada, CLI 1-76, Atmospheric and Environmental Services, Downsview, Ontario, Canada, 151 pp.

Jahne, B., 1991. New experimental results on the parameters influencing air-sea gas exchange. In: *Air-Water Mass Transfer*. S.C. Wilhelms and J.S. Gulliver (Eds.), ASCE, New York, NY, p. 528-592.

Jones, M., D. Stewart, R. O'Gorman, E. Mills, O. Johannsson, W. Sprules and S. Millard, 1992. *Status of the Lake Ontario offshore pelagic fish community and related ecosystem in 1992*. A report prepared at the request of the Lake Ontario Committee of the Great Lakes Fishery Commission, 34 pp.

Kerr, S.J. and G.C. LeTendre, 1991. *The state of the Lake Ontario fish community in 1989*. Great Lakes Fishery Commission Special Publication, p. 91-93.

Kitaigorodskii, S.A., M.A. Donelan, J.L. Lumley and E.A. Terray, 1983. Wave turbulence interactions in the upper ocean. Statistical characteristics of wave and turbulent components of the random velocity field in the marine surface layer. *Journal of Physical Oceanography*, **13**, 1988-1999.

Kitchell, J.F. and S.R. Carpenter, 1987. Piscivores, planktivores, fossils and phorbins. In: *Predation: Direct and Indirect Impacts on Aquatic Communities*. W.C. Kerfoot and A. Sih (Eds.), Hanover University Press of New England.

Klump, J.V., R. Paddock, C.C. Remsen, S. Fitzgerald, M. Boraas and P. Anderson, 1989. Variations in sediment accumulation rates and the flux of labile organic matter in eastern Lake Superior basins. *Journal of Great Lakes Research*, **15**, 104-122.

Kolber, Z., R.T. Barber, K.H. Coale, S.E. Fitzwater, R.M. Greene, K.S. Johnson, S. Lindley and P.G. Salkowski, 1994. Iron limitation of phytoplankton photosynthesis in the equatorial Pacific Ocean. *Nature*, **371**, 145-149.

Larsen, I. H., 1994. *Biogeochemical cycling of phosphorus in Lake Michigan during the spring phytoplankton bloom*. M.S. Thesis, University of Wisconsin, Milwaukee, 131 pp.

Lasker, R., 1978. The relation between oceanographic conditions and larval anchovy food in the California Current: Identification of factors contributing to recruitment failure. *Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer*, **173**, 212-230.

Leach, J.H., 1993. Impacts of the zebra mussel (*Dreissena polymorpha*) on water quality and fish spawning reefs in western Lake Erie. In: *Zebra Mussels: Biology, Impacts, and Control*. T.F. Nalepa and D.W. Schloesser (Eds.), Lewis Publishers, Chelsea, MD, p. 381-397.

Lehman, J.T., 1991. Causes and consequences of cladoceran dynamics in Lake Michigan: implications of species invasion by Bythotrephes. *Journal of Great Lakes Research*, **17**, 437- 445.

Lehman, J.T. and C.E. Caceres, 1993. Species invasion and food web changes by a predatory invertebrate: Bythotrephes in Lake Michigan. *Limnology and Oceanography*, **37**, 879-891.

Lesht, B.M. and N. Hawley, 1987. Near-bottom currents and suspended sediment concentration in southeastern Lake Michigan. *Journal of Great Lakes Research*, **13**, 375-386.

MacIntyre, S., R. Wanninkhof and J.P. Chanton, 1995. Trace gas exchange across the air-water interface in freshwater and coastal marine environments. In: *Methods in Ecology: Trace Gases* (Chapter 3). P. Matson and R. Harriss (Eds.), Blackwell.

Mackie, G.L., 1991. Biology of the exotic zebra mussel, *Dreissena polymorpha*, in relation to native bivalve and its potential impact in Lake St. Clair. *Hydrobiologia*, **219**, 251-268.

MacLennan, D.N. and E.J. Simmonds, 1992. *Fisheries Acoustics*. Chapman and Hall, London, 325 pp.

Manchester-Neesvig, J. and A.W. Andren, 1989. Seasonal variation in the atmospheric concentration of PCB congeners. *Environmental Science and Technology*, **23**, 1138-1148.

Mason, D.M. and E.V. Patrick, 1993. A model for the space-time dependence of feeding for pelagic fish populations. *Transactions of the American Fisheries Society*, **122**, 884-901.

McDonald, M.E., L.B. Crowder and S.B. Brandt, 1990. Changes in *Mysis* and *Pontoporeia* populations in southeastern Lake Michigan: A response to shifts in fish community. *Limnology and Oceanography*, **35**(1), 220-227.

Moll, R. and M. Brahce, 1986. Seasonal and spatial distribution of bacteria, chlorophyll, and nutrients in nearshore Lake Michigan. *Journal of Great Lakes Research*, **12**, 52-62.

Mortimer, 1981. *The Lake Michigan Pollution Case: A Review and Commentary on the Limnological and Other Issues*. Wisconsin Sea Grant publication # WIS-SG-81-237, 156 pp.

Mortimer, C.H., 1988. Discoveries and testable hypotheses arising from coastal zone color scanner imagery of southern Lake Michigan. *Limnology and Oceanography*, **33**(2), 203-226.

Nalepa, T.F. and D.W. Schloesser, 1992. In: *Zebra Mussels: Biology, Impacts and Control*. Lewis Publishers, 810 pp.

National Oceanic and Atmospheric Administration, GLERL, 1992. *Proceedings of the Great Lakes - Coastal Ocean Program Workshop on Forming an Initiative Coastal Zone Management and the Laurentian Great Lakes*. November 5-6, 1992, Ypsilanti, MI. Cooperative Institute for Limnology and Ecosystem Research, University of Michigan and NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI.

National Oceanic and Atmospheric Administration, NOS, 1986. *Great Lakes water levels, 1860-1985*. NOAA National Ocean Survey, Silver Springs, MD.

National Research Council, 1994. *Priorities for Coastal Ecosystem Science*. National Academy Press, Washington, D.C.

National Science Foundation Report, 1987. *Basic issues in Great Lakes research*. Proceedings of Workshop, Kellogg Biological Station, Hickory Corners, MI. Special Report #123, Great Lakes Research Division, University of Michigan, Ann Arbor, MI.

Nichols, K.H. and G.J. Hopkins, 1993. Recent changes in Lake Erie (north shore) phytoplankton: cumulative impacts of phosphorus load reductions and the zebra mussel introduction. *Journal of Great Lakes Research*, **19**, 637-647.

Nurnberg, G.K., 1984. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. *Limnology and Oceanography*, **29**, 111-124.

Ocampo-Torres, F.J., M.A. Donelan, N. Merzi and F. Jia, 1994. Laboratory measurements of mass transfer of carbon dioxide and water vapor for smooth and rough flow conditions. *Tellus*, **46B**(1), 16-32.

Olivarez, A.M., R.L. Owen and D.T. Long, 1989. Geochemistry of rare earth elements in benthic layer particulate matter and sediments of Lake Superior. *Journal of Great Lakes Research*, **15**, 59-67.

Oviatt, C.A., C.D. Hunt, G.A. Vargo and K.W. Kopchynski, 1981. Simulation of a storm event in marine microcosms. *Journal of Marine Research*, **9**, 605-626.

Quigley, M.A., 1988. Gut fullness of the deposit-feeding amphipod, *Pontoporeia hoyi*, in south-eastern Lake Michigan. *Journal of Great Lakes Research*, **14**, 178-187.

Quigley, M.A., W.S. Gardner and W.M. Gordon, 1993. Metabolism of the zebra mussel (*Dreissena polymorpha*) in Lake St. Clair of the Great Lakes. In: *Zebra Mussels: Biology, Impacts, and Control*. T.F. Nalepa and D.W. Schloesser (Eds.), Lewis Publishers, Chelsea, MD, p. 295-306.

Rea, D.K., R.L. Owen and P.A. Meyers, 1981. Sedimentary processes in the Great Lakes. *Reviews of Geophysics and Space Physics*, **19**(4), 635-648.

Rhoads, D.C., K. Tenore and M. Browne, 1975. The role of resuspended bottom mud in nutrient cycles of shallow embayments. In: *Estuarine Processes*. L.L. Cronin, (Ed.), Academic Press, New York and London, p. 563-579.

Ritzrau, W. and G. Graf, 1992. Increase of microbial biomass in the benthic turbidity zone of Kiel Bight after resuspension by a storm event. *Limnology and Oceanography*, **37**, 1081-1086.

Robbins, J.A. and B.J. Eadie, 1991. Seasonal cycling of trace elements 137Cs, 7Be, and 239+240 Pb, in Lake Michigan. *Journal of Geophysical Research*, **96**(C9), 17081-17104.

Robinson, A.R., 1983. *Eddies in Marine Science*. Springer-Verlag, New York, p. 173.

Rosa, F., 1985. Sedimentation and sediment resuspension in Lake Ontario. *Journal of Great Lakes Research*, **11**, 13-25.

Salmun, H., P.D. Killworth and J.R. Blundell, 1991. A two dimensional model of boundary mixing. *Journal of Geophysical Research*, **96**, 18447-18474.

Sandilands, R.G. and A. Mudroch, 1983. Nepheloid layer in Lake Ontario. *Journal of Great Lakes Research*, **9**, 190-200.

Sanford, L.P., 1992. New sedimentation, resuspension, and burial. *Limnology and Oceanography*, **37**, 1164-1178.

Sato, G.K. and C.H. Mortimer, 1975. *Lake Currents and Temperature Near the Western Shore of Lake Michigan*. University of Wisconsin-Milwaukee, Special Report No. 22, 98 pp.

Saylor, J.H., J.C. Huang and R.O. Reid, 1980. Vortex modes in southern Lake Michigan. *Journal of Physical Oceanography*, **10**, 1814-1823.

Scavia, D. and G.A. Laird, 1987. Bacterioplankton in Lake Michigan: dynamics, controls and significance to carbon flux. *Limnology and Oceanography*, **32**, 1017-1033.

Scavia, D., G.L. Fahnenstiel, M.S. Evans, D.J. Jude and J.T. Lehman, 1986. Influence of salmonine predation and weather on long-term water quality trends in Lake Michigan. *Canadian Journal of Fisheries and Aquatic Sciences*, **43**, 435-443.

Scavia, D. and G.L. Fahnenstiel, 1987. Dynamics of Lake Michigan phytoplankton: mechanisms controlling epilimnetic communities. *Journal of Great Lakes Research*, **13**, 103-120.

Schwab, D.J., 1992. Hydrodynamic modeling in the Great Lakes from 1950 to 1990 and prospects for the 1990s. In: *Chemical Dynamics in Fresh Water Ecosystems*. F.A.P.C. Gorbas and J.A. McCorquodale, (Eds.), Lewis Publishers, Ann Arbor, MI, p. 41-62.

Schwab, D.J. and K.W. Bedford, 1994. Initial implementation of the Great Lakes forecasting system: a real-time system for predicting lake circulation and thermal structure. *Water Pollution Research Journal of Canada*, **29**, 203-220.

Schwarzenbach, R., P. Gschwend and D. Imboden, 1993. *Environmental Organic Chemistry*. Wiley & Sons, Inc., New York, NY, 781 pp.

Scott, J.T., P. Jekel, and M.W. Fenlon, 1971. Transport in the baroclinic coastal current near the south shore of Lake Ontario in early summer. In: *Proceedings of the 14th Conference of Great Lakes Research*, International Association of Great Lakes Research, Ann Arbor, MI, p. 640-653.

Simons, T.J., 1983. Resonant topographic response of nearshore currents to wind forcing. *Journal of Physical Oceanography*, **13**, 512-523.

Simons, T.J. and W.M. Schertzer, 1985. Stratification, currents, and upwelling in Lake Ontario, summer 1982. *Canadian Journal of Fisheries and Aquatic Sciences*, **44**, 2047-2058.

Simons, T.J. and W.M. Schertzer, 1985. *The circulation of Lake Ontario during the summer of 1982 and the winter of 1982-1983*. Environment Canada, National Water Research Institute, Contribution 85-26, Burlington, Ontario, Canada.

Simons, T.J., C.R. Murthy and J.E. Campbell, 1985. Winter circulation in Lake Ontario. *Journal of Great Lakes Research*, **11**, 423-433.

Sklar, F.H. and R. Costanza, 1991. The development of dynamic spatial models for landscape ecology: A review and prognosis. *Ecological Studies Analysis and Synthesis*, **82**, 239-288.

Smith, R.L. and K.H. Brink, 1994. *Coastal Ocean Processes: Wind-Driven Transport Processes on the U.S. West Coast*. Coastal Ocean Processes Report No. 4, WHOI-94-20, Woods Hole Oceanographic Institution, Woods Hole, MA.

Sprules, W.G., S.B. Brandt, E.H. Jin, M. Munawar, D.J. Stewart and J. Love, 1991. Patterns in the biomass size structure of the total Lake Michigan pelagic community. *Canadian Journal of Fisheries and Aquatic Sciences*, **48**(1), 105-115.

Sterner, R.W., 1989. Resource competition during seasonal succession toward dominance by cyanobacteria. *Ecology*, **70**, 229-245.

Sterner, R.W., 1990. The ratio of nitrogen to phosphorus resupplied by herbivores: zooplankton and the algal competitive arena. *American Naturalist*, **136**, 209-229.

Strub, P.T., P.M. Kosro, A. Huyer, 1991. The nature of the cold filaments in the California Current system. *Journal of Geophysical Research*, **96**(C8), 14743-14768.

Taghon, G.L., A.R.M. Nowell and P.A. Jumars, 1980. Induction of suspension feeding in spionid polychaetes by high particulate fluxes. *Science*, **210**, 562-564.

Talhelm, D.R., 1988. *Economics of Great Lakes Fisheries: A 1985 Assessment*. Great Lakes Fishery Commission, Technical Report 54.

Taylor, P.A. and R.J. Lee, 1984. Simple guidelines for estimating wind speed variations due to small-scale topographic features. *Climatology Bulletin*, **18**, 3-32.

Tenore, K.R., 1977. Food chain pathways in detrital feeding benthic communities: a review, with new observations on sediment resuspension and detrital recycling. In: *Ecology of Marine Benthos*. B.C. Coull, (Ed.), University of South Carolina Press, Columbia, SC, p. 37-53.

Terray, E.A., M.A. Donelan, Y. Agrawal, W.M. Drennan, K.K. Kahma, A.J. Williams III, P.A. Hwang and S.A. Kitaigorodskii, 1995. Estimates of kinetic energy dissipation under breaking waves. *Journal of Physical Oceanography*, in press.

Thomas, R.L., 1972. Distribution of mercury in the sediments of Lake Ontario. *Canadian Journal of Earth Sciences*, **9**, 636-651.

Thomas, R.L., 1983. Lake Ontario sediments as indicators of the Niagara River as a primary source of contaminants. *Journal of Great Lakes Research*, **9**, 118-124.

Tilzer, M.M. and P. Bossard, 1992. Large lakes and their sustainable development. *Aquatic Sciences*, **54**, 91-103.

Turner, M.G. and R.H. Gardner, 1991. Quantitative methods in landscape ecology: The analysis and interpretation of landscape heterogeneity. *Ecological Studies*, Springer-Verlag, New York, Vol. 82, 536 pp.

Twinch, A.J. and R.H. Peters, 1984. Phosphorus exchange between littoral sediments and overlying water in an oligotrophic north-temperate lake. *Canadian Journal of Fisheries and Aquatic Sciences*, **41**, 1609-1617.

U.S. Fish and Wildlife Service, 1990. *The Challenge: Restoring the Great Lakes*. U.S.F.W.S. Great Lakes Initiative, 17 pp.

U.S. GLOBEC, 1972. *GLOBEC Northwest Atlantic Implementation Plan Report # 6*. U.S. Global Change Research Program, U.S. GLOBEC Office, Dept. of Integrative Biology, University of California, Berkeley, CA.

Vanderploeg, H.A., W.S. Gardner, C.C. Parrish, J.R. Liebig and J.F. Cavaletto, 1992. Lipids and life-strategy of a hypolimnetic copepod in Lake Michigan. *Limnology and Oceanography*, **37**, 413-424.

Viekman, B.E., R.D. Flood, M. Wimbush, M. Faghri, Y. Asako and J.C. Van Leer, 1992. Sedimentary furrows and organized flow structure: A study in Lake Superior. *Limnology and Oceanography*, **37**, 797-812.

Wainwright, S.C., 1987. Stimulation of heterotrophic microplankton production by resuspended marine sediment. *Science*, **238**, 1710-1711.

Wainwright, S.C., 1990. Sediment-to-water fluxes of particulate material and microbes by resuspension and their contribution to the planktonic food web. *Marine Ecology Progress Series*, **62**, 271-281.

Wetzel, R.G., 1983. *Limnology*. Saunders College Publishing, Philadelphia, PA, 2nd edition.

Wu, 1975. Wind-induced drift currents. *Journal of Fluid Mechanics*, **68**, 49-70.

Acknowledgments

We would like to thank the individuals at the Center for Great Lakes Studies, University of Wisconsin-Milwaukee, for their assistance in hosting the workshop; the Chairs and Rapporteurs of the working groups; the reviewers; and all those individuals who participated in the October workshop.

The support for the printing of this Great Lakes Report has been provided by the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory (NOAA GLERL), and the Office of Naval Research (ONR) Funding was administered through NSF Grant No. OCE-9321430, NOAA GLERL Grant No. 40WCNR501683, and ONR Grant No. N00014-95-1-0454.

Appendix 1: Abstracts of Keynote Addresses

Overview of Cross-Shelf Transport in the Great Lakes

Alan Bratkovich and Guy Meadows, presenters

The Great Lakes basin lies beneath the polar front much of the year and hence is subjected to extremes in atmospheric forcing. The annual thermal cycle is characteristic of temperate regions with extremes in both summer heating and winter cooling. The temperature extremes result in a forced response of the Lakes which vary on daily, seasonal, annual and long period time scales. Similarly, the wind events which occur over the region are intense, frequent and rapidly evolving in both space and time. Hence, forcing due to episodic events plays a major role in the dynamics of the Great Lakes system and, hence, in the dynamics of cross-shelf transport processes.

Steady over water winds greater than 70 knots (35 m/s) with embedded gusts in excess of 80 knots (40 m/s) are not uncommon over the Great Lakes. These extreme events are often coupled with air-sea temperature differences greater than 11°C. These conditions can result in significant wave heights greater than 10 meters, seiche amplitudes greater than 5 meters and large pulses in circulation and internal modes within the basin.

Similarly, long period events contribute to the dynamics of the lakes. Mean water levels rise and fall as much as 2 meters over the span of a few years. Recent research shows that increased water levels are accompanied by an increase in wave energy and hence, increased surface forcing. Thus, it is not only the mean water level at the coastal boundary that is elevated, but there is also an increase in the forcing accompanying that elevation.

It is the general belief around the Great Lakes research community that these episodic events, over a wide range of temporal scales, are the major energetic factors which control nearshore dynamics. Studies involving research on sedimentation, resuspension and transport of particulates, bottom boundary layer processes, coastal currents, coastal erosion, frontal processes and ice are required to address the critical physical process issues facing this region.

In this presentation, we examine the dominant cross-shelf processes, how they occur in physical terms, and why they are important from the Great Lakes research perspective. Examples of mechanisms of cross-shelf processes are examined and basic unanswered research questions are raised.

Significant cross-shelf transport exists within the Great Lakes basin through many complicated processes. Additional perturbations in the nearshore region occur as a result of riverine run-off volume changes, surface induced factors such as upwelling and downwelling, and bottom boundary layer interactions. These convective motions become extremely important sources of contaminants. Under these conditions, particles are not simply diffused across the coastal boundary layer into the deep lake, but are strongly affected by the interactions of coastal circulation.

In the Great Lakes region, the primary source of material which eventually settles in the deep basin is derived from coastal erosion. Substantial coupling exists between nearshore and coastal boundary layer flows. The response of the coastal boundary layer to environmental forcing is rapid, on the order of hours. In this realm, boundary stresses and pressure gradients dominate the physical setting. Cross-shelf flow reversals and strong horizontal shears are common.

The major research questions facing cross-shelf transport in the Great Lakes are:

1. What role do frontal features or coastal/offshore contrasts play in particle distributions/ fluxes, fish, bioenergetics or early life history?

2. How do sediments or particles of coastal origin reach offshore burial sites?

3. Do anomalous seasonal/annual signals cause significant lake-wide or basin-wide ecosystem changes?

4. What types of episodic events are most effective at transporting or transforming constituents of coastal origin?

These questions must be addressed in terms of the extreme and episodic nature of Great Lakes forcing and within the variability associated with daily, seasonal, annual and long time scale forcing variations which are so much a history of this dynamic region.

Air-Sea Interactions in the Coastal Oceans

Mark A. Donelan, presenter

The coastal zone is a region of rapid change in many air-water interaction processes. In offshore winds, the air encounters a sudden change in surface characteristics and the development of a new (internal) boundary layer in the air flow has important consequences in many air-water interaction processes. At the same time the generation of ripples and subsequent growth of waves are strongly dependent on the fetch (distance offshore). At short fetch, these developing waves are the boundary roughnesses and so one might expect significant changes in the stress (momentum transfer) applied by the wind to the water and the consequent generation of currents and initiation of internal waves, seiches, etc.

Onshore winds, on the other hand, have become adjusted to the lake surface and the atmospheric boundary layer is well developed. However, the wave field undergoes rapid modification as the depth is reduced and the changes in propagation velocity and steepness of the shoaling waves produce significant changes in the surface characteristics, albeit more slowly than the land/water discontinuity in the case of offshore winds.

In this overview presentation, I will focus on these special air-water interaction characteristics that occur in the coastal zone.

Wind and wave development

Meteorological information is available at many sites around the Great Lakes and one would like to be able to use these land-based winds for estimating the surface interactions on the lake. As the air flows from land to water, the roughness decreases abruptly at the shore, and, as the waves develop, increases again for some distance offshore. Further offshore the propagation speed of the largest waves becomes comparable with the wind speed and the roughness decreases again. The change in wind speed at anemometer height (10 m) caused by these roughness changes has been calculated by Taylor and Lee (1984) through the development of an internal boundary layer in which the imposed stress at the top of the boundary layer is assumed to remain constant. Figure 1 gives an example of the calculated variation in wind speed at 10m in an offshore wind.

The waves develop offshore, increasing in height, period and propagation speed (Figure 2). Donelan (1990) has shown that the roughness to wave height ratio depends on the inverse wave age in the following way:

$$z_0 = 5.53 \times 10^{-4} \sigma (U_{10}/c_p)^{2.66}$$

where z_0 is the roughness length, σ the rms wave height and c_p the phase speed of the waves at the spectral peak. The calculated changes in the wave age and drag coefficient with fetch are shown in Figure 3.

Energy dissipation in the surface layers

In very light winds (<2 m/s) the wind stress is communicated to the surface by viscous forces and the energy flux is from wind to surface currents. The resulting drift current speed at the surface is about one-half the friction velocity in the air (Wu, 1975). Under these circumstances, of aerodynamically smooth flow, the energy flux from air to water is proportional to the friction velocity cubed. On the other hand, when the wind is strong (>7 m/s), most of the stress is generated by interaction with surface roughnesses, i.e., waves of various lengths. Some of the resulting momentum transfer is retained by the waves and advected away as the waves' momentum increases downwind. However, various estimates of the retained momentum put it at less than 10% decreasing to 0% as the waves approach full development. The other 90% or more is converted to current momentum as the waves break and the energy flux is now much larger since the transfer of energy and momentum is actually to waves with much larger propagation velocity than the friction velocity (Terray et al., 1995). Under these circumstances, of aerodynamically rough flow, the energy flux from air to water is proportional to the friction velocity squared times an average phase velocity for the roughness elements, i.e., waves. The waves, in breaking, inject kinetic energy into the upper layers and it should come as no surprise that the kinetic energy dissipation near the surface can be much larger than would occur in smooth flow. Experimental evidence for this has been presented by Kitaigorodskii et al. (1983) and Agrawal et al. (1992). Figure 4, reprinted from Agrawal et al. illustrates the occurrence of dissipation rates near the surface that are 10-100 times larger than wall layer estimates.

The enhanced level of turbulent kinetic energy in the surface waters has important consequences for many processes including thermocline development and gas transfer at the surface.

Gas transfer

The process of gas transfer between air and water is most conveniently described in terms of a four layer structure (Figure 5). In the bulk of the boundary layers on both sides of the interface turbulence dominates the mixing and the transfer is efficient, leading to weak gradients. Near the interface, the turbulence is suppressed and in these very thin layers the transfer is via molecular processes and consequently the gradients are much larger. The resistance to transfer is principally in these thin diffusive layers. When the resistance is larger in the diffusive boundary layer above the surface, transfer of the gas is said to be under gas phase control; when the principal resistance is below the interface transfer is under liquid phase control. Highly soluble or reactive gases such as SO_2, SO_3, NH_3 and H_2O are under gas phase control, while less soluble gases such as O_2, N_2, CO_2, CO, CH_4 are under liquid phase control.

Gas phase controlled transfer is enhanced by high turbulence intensities in the air near the surface, while liquid phase controlled transfer is more closely related to turbulence beneath the surface. The level of turbulence in the air is due to the wind shear and is roughly proportional to the wind speed, while in the water there are two sources of turbulence: that due to the shearing of the drift current and that due to the injection of turbulence by wave breaking. Ocampo-Torres et al. (1994) have explored the changes in mass transfer coefficient for water vapor and carbon dioxide, the former being gas phase controlled while the latter is liquid phase controlled. Their results, summarized in Figure 6, show clearly the greater sensitivity to wind speed of carbon dioxide transfer. The rapid increase in the bulk transfer coefficient coincides with the appearance of breaking of the small waves. These are laboratory measurements and we are currently extending our measurements to include direct and simultaneous flux measurements of carbon dioxide and water vapor on Lake Ontario with concomitant measurements of wind stress and kinetic energy dissipation in the water. Our measuring platform is mobile (a launch), thereby allowing us to explore the effects of rapid changes in the wave field on gas transfer and kinetic energy dissipation in the epilimnion.

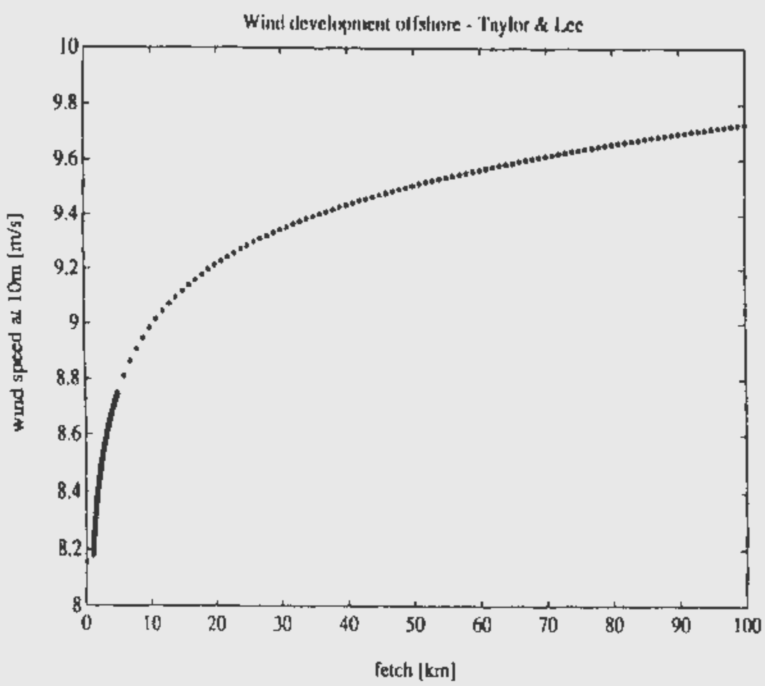


FIGURE 1. Development of the 10m height wind speed in an offshore wind as calculated by the Taylor and Lee (1984) algorithm.

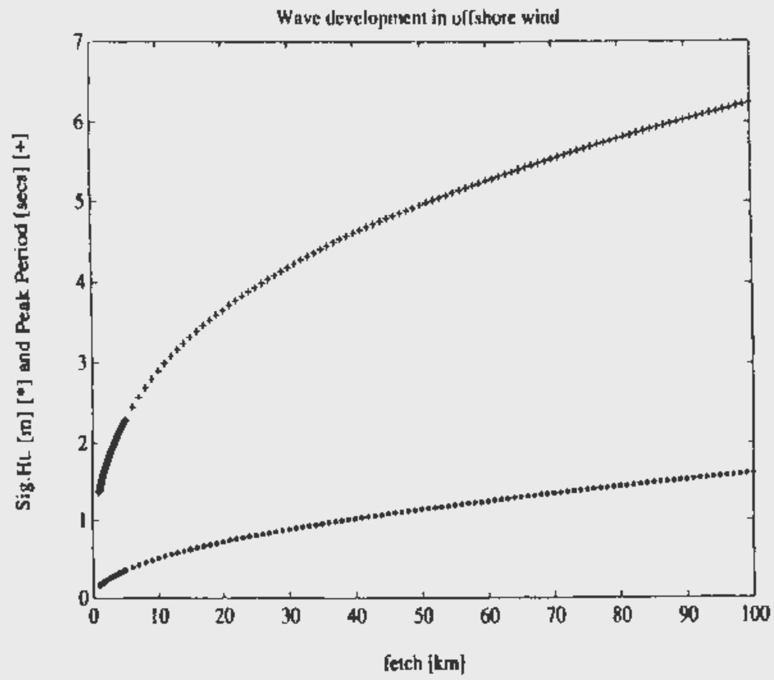


FIGURE 2. Development of wave properties with fetch in response to the winds of Figure 1.

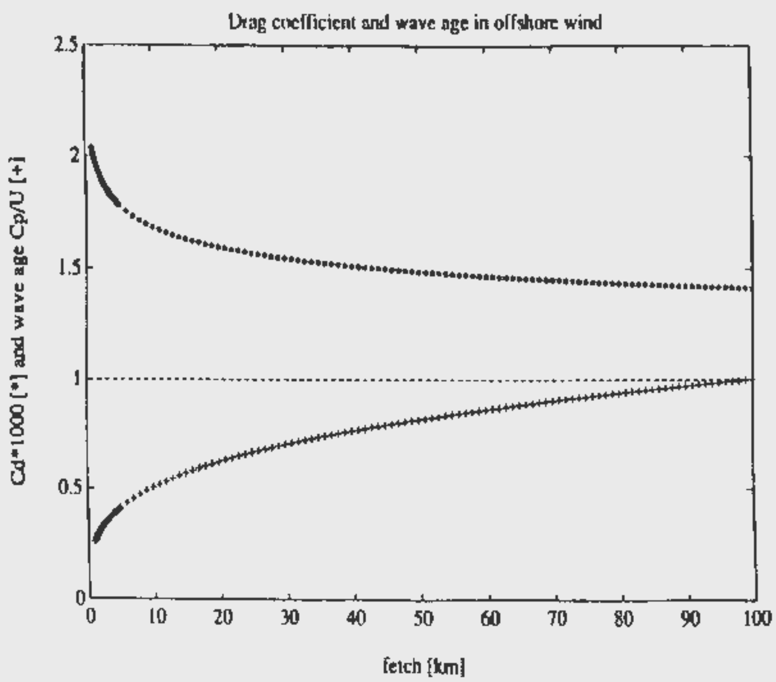


FIGURE 3. Changes in the wave age and drag coefficient with fetch in response to the winds of Figure 1.

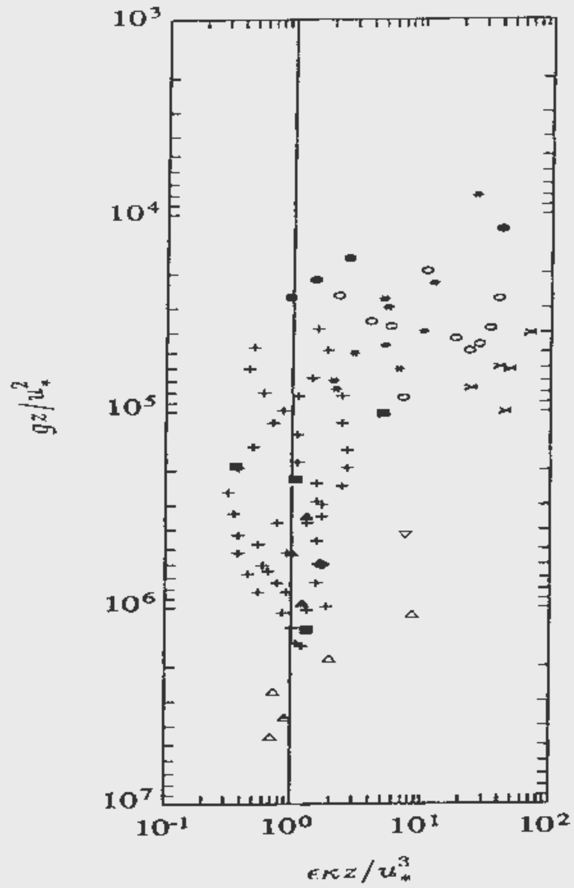


FIGURE 4. Kinetic energy dissipation in wall layer coordinates. The prediction of wall layer theory appears as the vertical line. The data are drawn from various oceanographic and limnological sources. (Agrawal et al., 1992)

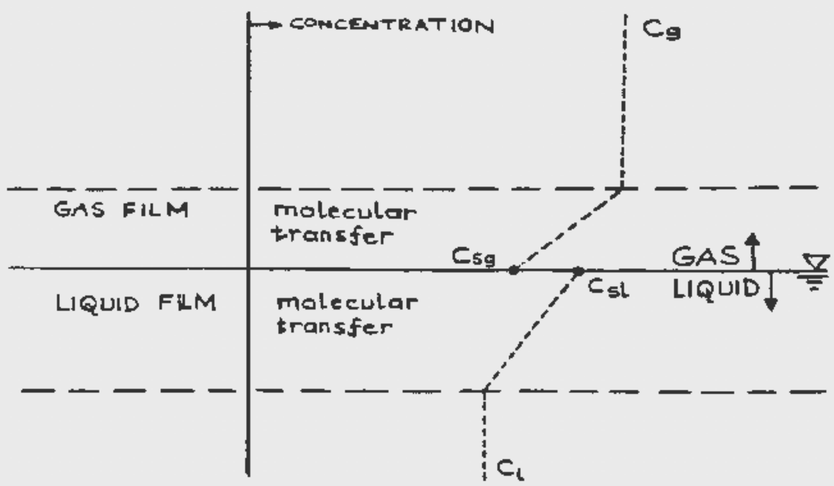


FIGURE 5. Schematic diagram of the four layer structure relevant to gas transfer across the air-water interface.

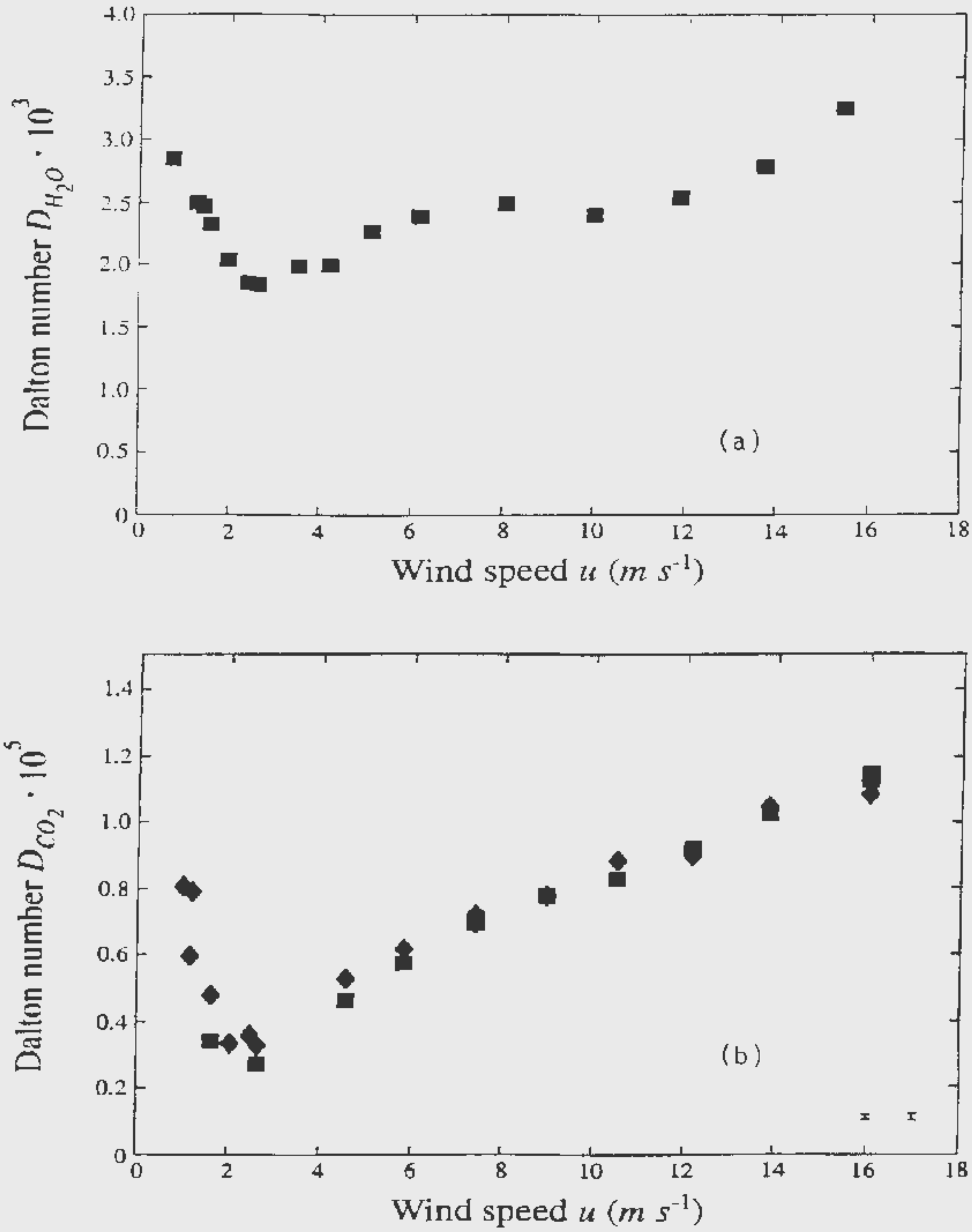


FIGURE 6. Laboratory measurements of the bulk transfer coefficient (Dalton number) for water vapor (a) and carbon dioxide (b). (Ocampo-Torres et al., 1994)

What Drives Biological Production in the Great Lakes?: Linking the Physics and Chemistry to the Biology

Stephen B. Brandt, presenter

The biological communities of each of the Great Lakes have undergone dramatic changes over the past 100 years. The changes have been caused by a combination of habitat alteration, eutrophication, commercial fishing, invasions of exotic species, purposeful species introductions and natural variability. Present-day management efforts are largely focused on reducing the nutrient and contaminant loading to the lakes, rehabilitating some of the native fish populations, stabilizing the recreational and commercial fisheries, restoring habitats or minimizing further habitat degradation and limiting the continuing invasion of exotic species. The nutrient management strategies set forth in the 1972 Great Lakes Water Quality Agreement have been particularly successful at reducing the phosphorus loadings to the Great Lakes (e.g., Hartig et al., 1991). This success has led to questions about whether nutrient management has begun to interfere with fisheries management. Over the past 20 years, trout and salmon have been stocked at high rates in the Great Lakes to support a recreational fishery that has been valued at approximately $4 billion per annum (Talhelm, 1988).

Will nutrient reductions limit the production of fishes at the top of the food-web? A basic understanding of the interaction of food-web processes and the physical/chemical environment is required to answer this question. Production at any trophic level is clearly affected by food availability (resource regulation) and predation pressure from higher trophic levels (consumer regulation). These processes have been well documented in the Great Lakes (Kitchell and Carpenter, 1987; Evans, 1990; McDonald et al., 1990; Hartig et al., 1991). But production and biological rates are also affected by local environmental conditions (e.g., light, temperature, nutrient concentration) which can vary in time and space. The Great Lakes, in particular, are large and physically complex environments characterized by langmuir circulation cells, upwelling, internal seiches, river plumes, and seasonal changes in thermal structure. These physical processes set up a mosaic of environmental conditions and transport mechanisms that can significantly affect predator-prey interactions and production. Yet, estimates of biological production in the Great Lakes are often based on some lakewide measure of mean conditions; spatial complexity of the environment is ignored.

Water temperature is a key factor that sets the stage for biological production in the Great Lakes. The development of the seasonal thermocline, in particular, largely defines the bounds of nutrient cycling and limits the distributions and interactions of higher trophic levels (Brandt et al., 1980). For example, physiological processes of fishes are highly sensitive to water temperature and even small changes of 1-2°C can have profound effects on fish physiological rates (e.g., Bartell et al., 1986). Therefore, the rates that determine fish growth and production must be assessed at the local level. A similar argument could be made for other sensitive environmental conditions such as light levels which directly affect primary production or prey visibility in predator-prey interactions (Mason and Patrick, 1993).

Biological patchiness is also prevalent in the Great Lakes (e.g., Brandt et al., 1991; Sprules et al., 1991) and trophic interactions may be high in one region and low in another. For example, Lasker (1978) showed that survival and growtb of larval anchovies depended on the existence of ephemeral food patches; prey densities estimated from spatial averaging would lead to predator starvation. How do such local biological and physical conditions influence production at the ecosystem level, and how do we evaluate these scale-dependent processes? What is the appropriate spatial scale to assess prey densities and habitat conditions for estimating biological production? Can biological processes that occur at relatively small spatial scales (1 - 10 m^3) or over relatively short time intervals (minutes-days) significantly affect production at the system level or on an annual basis?

One approach to help assess the relationships between spatial patterning in the environment and ecological processes is the use of spatial modeling (Sklar & Costanza, 1991; Brandt et al., 1992). The basic concept of spatial modeling is to subdivide a heterogeneous habitat into small homogenous cells or volumes of water. Process-oriented simulation models of the same model structure are run in each cell but are parameterized according to the habitat conditions measured in each cell. The key advantage of this approach is that, if cell sizes are sufficiently small, environmental conditions within each cell will meet assumptions of homogeneity, thus simplifying the structure of the ecological models. Dynamic spatial modeling can be used to assess transport and movement among cells.

Spatial modeling has been particularly successful in terrestrial ecology (Turner and Gardner, 1991) because satellite remote sensing techniques have provided sufficient spatial data for the models. The same approaches can be used in aquatic environments with the aid of automated sensing devices that can measure the biological and physical heterogeneity under the surface of the water. High-frequency echo sounders, acoustic-Doppler current profilers, and towed plankton counters are all capable of providing the type of high-resolution, spatial data necessary for spatial modeling. In this presentation, I show how such spatial modeling approaches can be used to get a better estimate of potential fish production and to assess how biological processes interact with spatial/temporal heterogeneity in the physical habitat to affect predator-prey interactions, fish growth rates and, ultimately, fish production.

The fish component of the pelagic food web of Lake Ontario is relatively simple and consists of stocked salmonids (principally chinook and coho salmon) that feed mainly on the two dominant pelagic planktivores, the alewife, *Alosa pseudoharengus*, and rainbow smelt, *Osmerus mordax* (Brandt, 1986). Production of alewife and rainbow smelt in the lake has declined recently, apparently because of low prey availability and excessive predation by stocked salmonids (Jones et al., 1992). To avoid the complete collapse of these prey populations, annual stocking rates of salmonids in Lake Ontario were cut in half over a two year period. This reduced stocking level will likely cause severe economic losses to the communities surrounding the lake that have been bolstered by tourism and sport fishing (Kerr and Le Tendre, 1991). Thus, it is crucial that estimates of lake-wide production and trophic interactions be accurate.

Spatial modeling was used to calculate potential growth rates and production of salmonids in the lake. Fish growth rate is a key factor because it integrates biological and environmental components of the habitat, and directly affects fish production, survival and reproductive success. Fish growth rate is a balance between the amount of energy consumed by a fish and the amount of energy lost through respiration, egestion, and excretion. Fish growth rates thus depend on fish physiology, prey availability, and habitat conditions such as water temperatures. Most models that evaluate fish growth rate assume that prey densities and temperature conditions are homogenous in the environment. But, since most of the factors that regulate biological rates are non-linear, the use of mean conditions over a given body of water may lead to serious errors.

An example of spatially-explicit model of a 5 kg chinook salmon growth rate potential across Lake Ontario illustrates the basic approach. A north-south (62 km long, maximum depth 185 m) transect near the center of Lake Ontario was sampled at night during fall. Underwater acoustics was used to measure prey (alewife and smelt) densities and sizes throughout the water column on a near-continuous basis (e.g., Brandt et al., 1991; MacLennan and Simmonds, 1992). Acoustic data were divided into cells with a resolution of 1 m depth by 77 m along the transect. The resultant grid contained approximately 100,000 cells of data. These data are then linked with species-specific, physiological-based models of fish growth to estimate fish growth potential (Brandt et al., 1992). Bioenergetics and foraging models were run in each of these cells using measured prey densities and temperatures as input variables. The model output is a cross-sectional map of fish growth rates that would be achieved in each cell if the predator occupied that particular cell for some specified unit of time.

Results suggested that temperature, prey biomass, and salmonid growth rates were unevenly distributed throughout the transect, and spatial averages would fail to give an accurate picture of the predator-prey dynamics and encounter rates in Lake Ontario. Predators were found in only 8.1% and prey in 25.9% of the available water volume. Predators were largely concentrated near the thermocline and overlap between predator and prey was high (78%) (Goyke and Brandt, 1993). Only 22.6% of the volume of the lake would support any growth of salmon. Much of the transect volume would not support fish growth since prey were in low supply and/or temperature conditions were not right. Overall, results showed that fish growth is sensitive to spatial patchiness in environmental (e.g., water temperature) and biological (prey densities) quantities and that scales of sampling and modeling must be adjusted accordingly. Large differences in estimates of fish production were found when physical and biological heterogeneity were included in the analyses (Brandt and Kirsch, 1993). These types of differences are unacceptable in tightly managed ecosystems.

Temporal variance in environmental conditions and in the distribution and densities of aquatic organisms may be as important as spatial variance in predator-prey interactions and production processes. Cyclical patterns and the pulsed forcing nature of ecosystems is more the rule than the exception (Glass and Mackey, 1988). The temporal analogues of physical-biological scale matching and their relationship to corresponding spatial scales need to be adequately evaluated. Temporal scales of physical and biological coupling may be event driven. For example, prey species may be concentrated in response to the seasonal development of the thermocline or transitory displacements of thermal gradients from upwelling caused by the passage of low-pressure storm systems. If predators are closely tracking prey, then the scale of temporal association between predator and prey will also shift. If the temporal scale of a feeding cycle changes with the passage of a storm event, then the frequency of events may influence consumption by predators.

In summary, the spatial and temporal complexity of the physical and biological structure in the Great Lakes sets up dynamic habitat conditions that directly affect production processes. Both sampling and modeling must be done at the appropriate spatial and temporal scales to effectively evaluate biological production. This will require the integration of new high-resolution sampling strategies with modeling techniques that account for heterogeneity in the environment.

Sediment Transport and Particle Dynamics

Keith W. Bedford, presenter

Just as there are interfaces between physical, biological and chemical processes in the nearshore zone, the ever shoreward progress of scientific experimentation presents interfaces, boundaries and choices in how to experimentally and analytically rationalize the nearshore zone. This is especially the case for the area of sediment transport and particle dynamics, the subject of this workshop overview presentation. With the CoOP goals in mind, this talk emphasizes four aspects: First, sediment transport processes are a key component of biological and chemical activity, deserving considerable measurement and analytical emphasis, yet we know only the most rudimentary knowledge about the physics of particle transport. Our measurement capability is even worse. Second, transport and reorganization of sediments in the nearshore zone is highly time varying and episodic and is dominate by transient pulses of particle fluxes over the six interfaces that define a nearshore volume or cell. Third, corresponding nearshore particle modeling becomes quite nonlinear and complex as the compressed spatial scales result in nonlinearly overlapping transport processes for which model parameterizations have not been field tested or, in some cases, not developed. Fourth, the interdisciplinary nature of the science problem can only be tackled by an interdisciplinary group of funding sources, most of which will be more applied and goal oriented than NSF. The explicit inclusion of the end user requirements and needs will be forced by these funding sources and therefore potentially new analysis frameworks and viewpoints will need to be adopted.

It is this last consideration that serves as the basis for the fundamental recommendation from the overview. It is recommended that the modeling approach be adopted early on in the development of the experiment and that the modeling framework be able to not only provide an improved science understanding of the observations made during the experiment but also leave behind a permanent improvement in the models used by mangers and decision makers. Such improvement can come in the form of improved confidence in existing models via field tests or new model structures or paradigms. Data collection therefore can be explicitly configured to address the numerical requirements of the adopted model and provide calibration tests for the improved model formulation or parameterization components of the model.

The remaining recommendations in this presentation center upon specific particle transport issues which must be addressed in order to pursue the prime recommendation above.

Four sediment transport model issues are defined. A required model component improvement focuses on the combining of Lagrangian and Eulerian viewpoints to create seamless coupled models of the water column and bottom sediments. Bottom models must be improved and coupled with the water column but the separate mathematical description procedures form a barrier to full coupling. Additional model components requiring improvement include descriptions of flocculation and disaggregation and the predictions (and measurement) of spatial and temporal distributions of grain size. Verified representations of the interaction of wave, turbulence and currents are required. This last item is especially urgent as the nearshore zone is approached and the effects of these three processes become more equal in magnitude. A final model component issue involves the possible inability to use Reynold's average as a definition of turbulence. This last issue is forced by the compression and overlap of highly transient transport processes in the nearshore zone and the possible inability to find a stationary averaging period.

General nearshore sediment transport science issues fall into three categories: (a) how and why does interfacial exchange occur as it is observed?; (b) what is the role of the small scale but intense sediment transport events on the large scale or macro-behavior of the overall lake?; and (c) how is the coupling between the biology and chemistry affected by the interaction between disruptive nearshore confined phenomena and the overall lake behavior? The occurrence of small scale disruptive particle transport results from the interaction of episodic events imposed at interfaces and stratification. The ubiquitous nearshore squirts and jets are documented usually through the use of remote sensing data. These phenomena also occur in other places as well, i.e., front occur in tributaries, especially during flow reversals and seiches, and tributary plumes become major "squirts" in the Lakes, especially after the passage of storms. Springtime thermal bars are also nearshore high gradient features modified by episodes and storms.

Application and implementation issues are eclectic. The first is the problem of developing new instruments to non-invasively and rapidly sample many of the small scale high gradient processes reviewed here. The recommendation is made to permanently install in the water continuous real-time readout water "weather" stations for permanent long term records. These data would contribute directly to the user and decision maker community who use long term probabilistic-based models for assessing risk. Long term sampling also suggests that surrogate measures need to be developed which allow more inexpensive measures of complex processes to be obtained.

The final application/implementation issue concerns the presence of the Great Lakes Forecasting System, an operational system for making regularly scheduled predictions of the hour-by-hour physical status of each of the Lakes. Suggestions are made that this system could serve as an excellent resource in configuring episode tracking or adaptive sampling. Furthermore, it could serve as the permanent system into which the post CoOP model improvements are infused.

Appendix 2: Reports of Working Groups

A. Coastal Currents and Coastal Jets

Chairperson: Barbara Hickey

Rapporteur: Tom Johnson

1.0 Background

The flux of suspended particles by coastal jets is a basic process affecting the biology, chemistry and geology of the Great Lakes. Alongshore jets may significantly affect the redistribution of material that enters the lake from point sources such as rivers, from distributed sources such as groundwater and from sediments resuspended from the lake floor.

Whole basin studies using moored current/temperature meters were performed in several of the Great Lakes in previous decades. These data have been used to examine aspects of the seasonal variation of the thermal front structure (e.g., Mortimer, 1988), the existence and nature of propagating waves (e.g., Saylor et al., 1980; Simons, 1983; Simons and Schertzer, 1985; Csanady, 1975) and the structure of the coastal jet (e.g., Blanton, 1974; Csanady and Scott, 1974). Although a reasonably comprehensive database is available in several of the lakes, insufficient data exist to make meaningful estimates of cross-shelf and alongshelf fluxes of suspended and dissolved material. Moreover, almost no data are available in the most energetic period (the winter season) when much of the particulate input to the lakes occurs. Finally, there is a lack of measurements sufficiently long term to address inter-annual variability of coastal systems within the Great Lakes.

2.0 Important Guiding Questions

An important aspect of the hydrodynamics of the Great Lakes is the existence of ice during the winter season. Ice may cover all or part of the surface of the Lakes and ice often fills the shallow regions very nearshore. The presence of ice can effect the development of coastal currents in several ways. For example, solid ice cover prevents the addition of momentum from the surface wind field to the coastal current system. Differential ice cover could generate significant wind stress curl, and hence upwelling or downwelling, in relatively small scale regions. Broken ice alters the surface stress by increasing surface drag, which subsequently results in a modification of the coastal current system. Ice along the coastline could inhibit the development of coastal currents through an increase in friction. The coastal jet is likely displaced seaward from its ice-free location.

thereby providing a mechanism for enhanced offshore transport. Most research to date on ice edge processes in the ocean has focused on deep water regions rather than the coastal zone. Finally, although it is always difficult to make measurements near and under ice, logistics are relatively simpler in the interior of the U.S. than in the Arctic or Antarctic. Thus from both a practical and a dynamical point of view the Great Lakes present a unique opportunity for research on ice effects on coastal currents.

Satellite-derived images of sea surface temperature in the Great Lakes suggest that eddies and meanders occur near the thermal bar and also in the region offshore of the coastal jet (Mortimer, 1988). Similar features in the coastal ocean have been related to the coastal jet or coastal front (e.g., Strub et al, 1991; Barth, 1994). The formation of such features in the ocean has been linked to coastal and bottom irregularities as well as to spatial gradients in wind stress. Whatever the formation mechanism, offshore squirts and meanders of fronts and coastal currents may provide an efficient mechanism for transfer of dissolved and suspended particulates, as well as organisms, from the nearshore region to deeper portions of the lakes. The discussions in our working group suggest that new research related to transport by coastal jets in the Great Lakes should focus on problems related to the existence of ice and/or meanders in the coastal current system. Specifically, we ask,

1. **How does the presence of ice in the Great Lakes affect the development, structure and the transport of coastal jets?**

2. **What is the role of meanders, jets and eddies related to the coastal jet in the cross-shelf flux of suspended and dissolved materials?**

3.0 Approach

3.1 Site Selection

The exact location of proposed studies was not discussed by our group. However, two important criteria for site selection were identified. First, the study should include both a Local Dynamics Experiment (LDE) and a larger scale study. If possible, there should be two LDEs, one in a region where upwelling is common, and the other in a region where downwelling is common. Second, because the lakes are closed systems, the group felt strongly that the larger scale study should include sampling of the entire lake on scales sufficient to resolve basin scale processes such as propagating waves. A schematic for a proposed study is shown in Figure 1. The exact placement and number of array elements was not addressed by the group. The discussion focussed on the overall concept of the proposal study.

3.2. Planned Observations/Data

Remote sensing of surface temperature and velocity fields, as well as visible imagery, may provide sufficient horizontal resolution and coverage to resolve the spatial scales of coastal features as well as their temporal scales. The limitation of such data is the lack of vertical resolution. However, when co-located with moorings and shipboard local surveys, this limitation can be ameliorated. Data from moored arrays of instrumentation generally provide excellent temporal resolution but comparatively poor spatial resolution. Shipboard surveys provide three dimensional snapshots of data fields. Information from all of these measurement techniques, when properly integrated, provides the most effective approach to study the highly time and space dependent problems relating to coastal fluxes of properties.

Satellite Data

Satellite-derived data are of primary importance for delineation of structures associated with coastal jets, and may be valuable in providing information on the wind field and currents. AVHRR surface temperature data are especially valuable in large lakes for two reasons: 1) in fresh water, the temperature field defines the density field; and 2) in the winter half of the year, the surface temperature represents the temperature of the entire water column in the coastal zone. Features resembling coastal current meanders and resulting squirts and eddies have been identified in AVHRR satellite images of the Great Lakes (e.g., Mortimer, 1988). CZCS measurements in the visible spectrum provide information on chlorophyll and suspended sediment concentrations in the surface waters. Microwave scatterometer data can be useful for interpolating between wind-measurement sites. The latest family of satellite altimeters, such as TOPEX/Poseidon and ERS-1, is capable of resolving water level variations of a few centimeters. Geostrophic currents can be inferred from these measurements, but the narrow width and shore proximity of the coastal jet may make it difficult to resolve this flow in the altimeter data.

High Frequency Radar Surface Current Measurements

Measurements of Doppler shifts in a back-scattered radar signal can be used to obtain the surface component of currents along the radar beam. With two well-separated radar systems, the two-dimensional surface current field is obtained. Currently available systems (OSCAR, CODAR) have ranges of about 30 km. Lower frequency systems with ranges up to 500 km are planned. Measurements by present systems are accurate to a few cm/s and have a spatial resolution of approximately 1 km. By using VHF instead of HF radar, resolution may be improved to 250 m at the expense of reducing the range to about 8 km.

Moored Instrumentation

An array of moored instrumentation (the Local Dynamics Experiment) would provide the long time series measurements needed to determine the mean circulation and the eddy fluxes of heat, mass, chemical and biological constituents. Such an array is important for resolving the horizontal scales and may permit calculation of local flux divergences responsible for dispersing or concentrating specific constituents within a limited region. A potential configuration for the moored array is shown in Figure 1. The between mooring spacing would be chosen to be less than the historically observed eddy scale. To understand the alongshore variability, a similar mooring array would be placed several eddy radii alongshore. Shipboard surveys would be used to spatially integrate the mooring data by providing a snapshot of the between mooring variability several times per year.

The lake scale variability of the coastal currents is also important. How do upwelling vs. downwelling regimes differ? What is the role of lake scale circulation, both wind-driven, and long wave-related, in the variability of the coastal currents? A minimum of two LDE arrays are needed to address these issues. Differences between upwelling and downwelling regimes are best addressed by placing the arrays on opposing sides of the lake being studied. Basin scale waves can be monitored by a more widely spread set of current meter moorings, with separations designed to resolve the spatial scales of the expected long waves adequately.

Lagrangian Drifters

Langrangian surface observations have been useful for identifying particle paths in ocean-based experiments investigating offshore transport by meanders and jets (Strub et al., 1991). We note that surface drifter tracks can significantly depart from particle tracks near fronts, where vertical transport is important. Nevertheless, we feel that deployment of arrays of Lagrangian drifters within the thermal bar and/or the coastal jet in concert with shipboard surveys would aid in the determination of probable pathways for dissolved and particulate material from the coast to the central basin.

Shipboard Surveys

Shipboard surveys are required to characterize the lake flow and water column within the LDE area and in the surrounding lake area. Within the LDE, side scan sonar and bathymetric/high-resolution seismic reflection surveys should he carried out to provide a detailed bathymetric map and to quantify bottom roughness features and regions of sediment accumulation. Water column measurements would include SeaSoar and ADCP surveys from a vessel that could be relatively small (e.g., R/V Laurentian). The vessel for these surveys should have sufficiently small draft to permit sampling in regions as shallow as 10 m of water. This vessel would carry out its surveys relatively rapidly by surveying continuously without stopping to collect water samples. A second, larger vessel would simultaneously carry out a sampling program for various water properties using CTD and water sampling bottles/pumps. On-board analyses for certain parameters would require a vessel with adequate lab space and capacity to carry 15 scientists. This vessel may be available from CCIW, EPA or an East Coast UNOLS institution. Four cruises per year are envisioned, to allow characterization of the water column in four seasons: spring bloom, summer stratification, late fall storms, and winter (if possible; may require an alternate platform, see below).

Sediment Sampling/Tracers

Sediment sampling within the LDE should include a surface grab-sampling program with sufficient sampling density to characterize the lake floor in terms of grain size, organic carbon content, and the presence of any potential natural tracer of sediment transport pathways (e.g., exotic minerals from nearby river). Labeled sediment could be introduced at a site within the LDE and tracked through time by a time series of surface sediment samples obtained on a predetermined grid. The initial surface sediment sampling program should be designed after careful analysis of the side-scan sonar and bathymetric survey data.

Long-Term Studies

Some measurement components should be maintained at selected sites beyond the one-year duration proposed for the overall study. The reasons are twofold: 1) to determine the interannual variability (and any shifts associated with climate change); and 2) to capture the rare extreme, e.g., the once-per-ENSO-cycle flood, the once-per-decade storm, etc. Measurement systems suitable for long-term installations include: 1) HF (or VHF) radar surface current measurements; 2) bottom-mounted ADCPs connected to shore by a cable (the cable provides power and returns the signals to shore for processing; such an installation can provide real-time data as well as allow rapid detection of instrument failure); and 3) additional sensors such as temperature and transmissivity, distributed throughout the water column, would also be required for long term studies.

3.3 Modeling Needs

While every proposed study of Great Lakes processes will benefit from a coordinated modeling study, those which deal with fluxes of material near the boundaries will depend rather substantially upon models. The objective of this overall study is to determine the cross-shelf transport of chemical, particulate and biological constituents; this includes both time-varying and mean fluxes. Our ability to measure currents for extended periods of time at a few points in the water column and at horizontally isolated moorings is quite good. Our ability to measure concentrations of chemical or biological constituents is less well developed. However, for some constituents, adequate long-term point measurements of the flux can be estimated, albeit with sparse spatial resolution. On the other hand, towed instrumentation may be able to estimate the flux with reasonably fine spatial resolution but poor time resolution. Unfortunately, we are interested in the net flux out of the coastal zone. Near the coast, topographically correlated fluxes are likely and the temporal average of these fluxes may be substantially larger than the along-coast mean. Therefore, small errors in our ability to measure or integrate these quantities may result in significant errors in our estimate of the cross-shelf flux. With some care, the fluxes within models can be calculated accurately with high spatial and temporal resolution. The trade-off is the realism of the model. It is only through the combination of model and data that we can have some confidence that the model is behaving in a manner consistent with the available data. This is not a call for data assimilation, rather a call for a carefully reasoned model-data comparison and consequent model improvement. For example, it is important that the models have energy on the time and space scales suggested by the data.

Three types of models, process, simulation and assimilation, would be useful for this study. Process models idealize some aspect of the problem; typically, the forcing and geometry are simplified. The advantage of such models is that they are relatively easy to implement and analyze. Of particular interest is the ability of these models to explore hypotheses for the existence of specific phenomena. This approach was used to substantial advantage for the development of the George's Bank study by U.S. GLOBEC (1992). Also, these models can be used to understand how the model physics is affected by changing the horizontal and vertical resolution. This task should not be overlooked as inadequate resolution is likely to be a serious shortcoming of any model.

Simulation models would attempt to reproduce the circulation of the lake when appropriately forced. These models should contain all of the essential physics (as identified from data and process models), have realistic topography, and be forced by realistic surface and boundary fluxes. However, the reality of computational limitations is such that these models cannot contain all of the essential physics which occur near the grid scale and smaller. As a result, some aspects of the behavior of these models are quite good; typically, the large scale wind-driven response or the tidal signal is well represented. However, good agreement at these scales is no guarantee at any other scale. This is particularly true when dealing with eddy fluxes, which may occur at smaller scales.

Assimilation models may be used to synthesize and interpolate appropriate data sets. In oceanographic situations, these models have proven to be valuable tools for interpolating between measurements both in space and time. The physics of these models need not be complete, because the data is used to control the evolution through time and space. The better the physics of the model, the less data is required to maintain a satisfactory field estimate. One reasonable scenario is that a data assimilation model could be used to describe the large scale structure of the lake circulation in order to set the context for the local dynamics experiments.

3.4 Instrumentation Needs

Selection of the specific instruments required at each mooring will depend on the question(s) selected for study. However a few general criteria can be identified. The large scale array needs relatively few (perhaps 2) instruments at most locations and only physical measurements (v, T). Eddy arrays must resolve both the stratified water column and the surface and bottom boundary layers (although perhaps not at all of the eddy moorings) and consequently require more intense sampling schemes. Time-dependent physical, chemical (O_2, NO_3,...), biological and particle (light transmission, backscatter) measurements must be made in these arrays. The need for year-round measurements and the desire for upper boundary layer measurements suggests that upper water column currents may best be measured by upward looking ADCPs. Because of the small time and space scales expected, a towed instrument package is needed (e.g., SeaSoar, etc.) to define the structure of the physical and biological (phytoplankton and zooplankton biomass) fields on relatively fine scales (1 km; 1 day). At the same time, water samples and net tows are required to do chemical analyses that are not possible with *in situ* sensors and also to determine species composition of the biomass.

3.5 Sampling Platforms

Research Vessels

Interdisciplinary research on the coastal jet will require the simultaneous use of two research vessels: one for rapid surveys with ADCP, SeaSoar, etc. and one for interdisciplinary water sampling and analyses, mooring deployment, etc. The latter must be equipped to support a relatively large, interdisciplinary group of scientists. The vessels must be capable of working in very shallow water (10 m). Access to vessels capable of working in winter and in partially ice-covered conditions will be required.

Helicopters

Ice covered conditions will require the use of platforms such as helicopters for wintertime sampling and deployment of instrument packages.

ROVs

Remotely controlled instrument packages may be particularly useful for under-ice investigations.

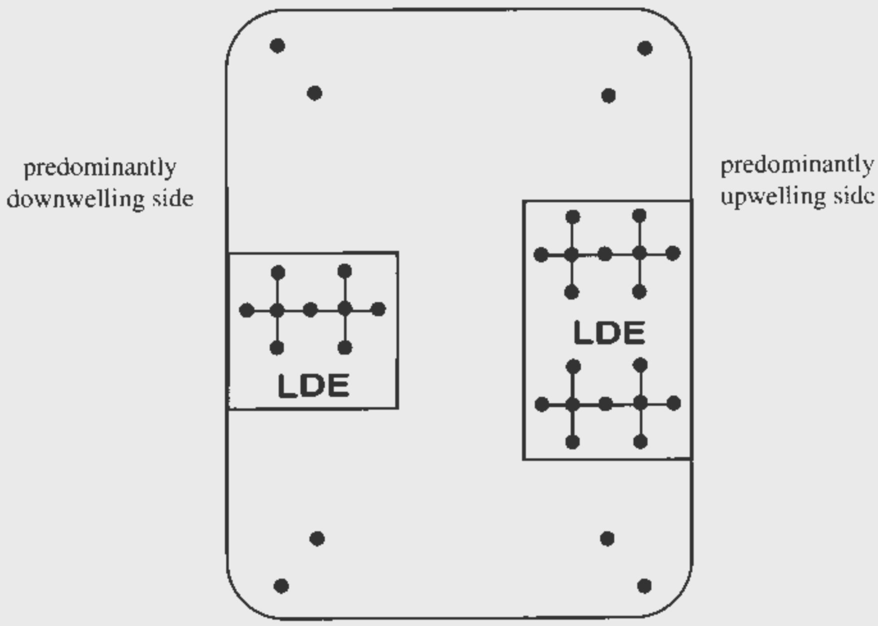


FIGURE 1. Generic Lake. (LDE = Local Dynamics Experiment; ●= moored arrays)

B. Thermal Fronts: Vernal Dynamics and Structure

Chairperson: Guy Meadows

Rapporteur: Steve Brandt

1.0 Background

The thermal regime of the Great Lakes is sufficiently harsh that temperature induced density fronts dominate the physical structure of the fluid. These frontal boundaries are particularly intense during the spring and fall transition periods. These time periods also correspond, in general, to periods of maximum evolution in the biological productivity at many levels in the trophic structure. Hence, there needs to be a complete understanding of the coupling of physical, biological and chemical processes in operation throughout the annual thermal cycle of the Great Lakes.

Large lakes in temperate regions undergo an intense and rapid transition from winter conditions (characterized by the surface at or below zero degrees C, with a thermal inversion with depth, approaching 4°C bottom water) to summer conditions (characterized by an intense thermocline with surface waters greater than 22°C and bottom waters remaining of 4°C). This shift in thermal regimes force and contribute to a number of periodically intense, density controlled circulations. Spring mixing, the development of the thermal har and periodic intersections of the seasonal thermocline with both the surface and nearshore bottom are examples of such events.

2.0 Important / Guiding Questions

Hence, the basic unanswered scientific questions concerning these processes are:

1. **How is the sequence of development of the thermal bar, developing thermocline, and episodic fluctuations linked to production dynamics in the Lake?**
2. **How do the various types of frontal processes caused by seasonal heating and cooling contribute to: production, trophic level development, material transformations (phytoplankton/fecal pellets/sedimentation) and cross-shore transport?**

3.0 Approach

3.1 Site Selection Criteria

The major basins of the Great Lakes offer both diversity as well as similarity. For this reason, both cross-lake and inter-lake comparisons of the development of the thermal structure are necessary. At opposite ends of the scale is Lake Superior, with its enormous thermal capacitance, contrasted with Lake Erie which exhibits rapid and intense thermal responses. Based upon these considerations and the general lack of background data for Lake Huron, inter-lake comparisons are recommended between Lakes Michigan and Ontario. Lakes Michigan and Ontario have similar topographic constraints and have enjoyed detailed previous investigations. Both lakes have very similar physical properties (e.g., surface to volume ratios), yet the nutrient forcing (external loading), is much higher in Lake Ontario. Lake Ontario also provided access and international scientific interest from Canada through the Canada Centre for Inland Waters (CCIW). The addition of the expertise and resources of CCIW would greatly enhance any U.S. Great Lakes scientific effort.

3.2 Planned Observations/Data

Storms and other episodic events are expected to play a major role in the development of the Lake-wide thermal structure. However, these episodes are the most difficult to observe with conventional ship-based sensors. Special opportunities exist within the Great Lakes to more fully utilize remote sensing techniques. Since the density field is uniquely determined by the temperature distribution, lake dynamics can be accurately inferred directly from space-borne or airborne remote sensors. Hence, these research investigations will rely heavily upon moored instrument arrays and remote sensing especially for cross-lake comparisons and evaluation of the effects of episodic events upon thermal structure progression.

3.3 Modeling Needs

With respect to modeling needs, again the Great Lakes offer unique opportunities over exposed oceanic coasts. The lakes are of sufficient dimensions to allow full, three-dimensional modeling at high resolution of whole lake physical and biological dynamics. Current numerical modeling efforts for the Great Lakes are highly advanced. Hence, the stage is set for numerical models to play a crucial role in both the design of high quality experimentation as well as in real-time experimental assimilation. This unique opportunity provides a very strong impetus for a successful integrated scientific effort in the Great Lakes. It is anticipated that a coordinated effort in this area could lead to the initial development and testing of coupled hydrodynamic and biologic models.

3.4 Instrumentation Needs

Investigations of vernal dynamics and structure require the development of no new instrumentation, methods, or platforms. Recent development of high resolution ADCPUs provide a proven and demonstrated technology for mapping of frontal development and structure. Similarly, acoustic methods of quantification of higher trophic level food web structure have also reached maturity. Newly developed and implemented real-time fluorescence techniques are also available for phytoplankton concentration mapping. Facilities with extensive experience in the acquisition and analysis of aircraft and satellite remotely sensed sea surface data exist within the Great Lakes basin. The coordinated use of these state-of-the-art technologies within the framework of an integrated Great Lakes experiment may provide great insight into coastal boundary layer dynamics in general.

3.5 Sampling Platforms

Research vessel support exists both on the Canadian and U.S. sides of the Great Lakes. These vessels are operated by Universities, U.S. and Canadian Government Laboratories and by private firms. In general, these vessels range widely in size and endurance, but are generally well equipped scientifically. Vessel availability has in the past heen excellent. Typical operations, again primarily because of the dimensions of the basins, have maximum duration of several days without a port call. Hence, even smaller vessels can play a major scientific role in Great Lakes field experimentation.

4.0 Summary

The intense and rapid fluctuations of the thermal signatures of the Great Lakes provide a unique opportunity to investigate the coupling of physical, chemical, geological and biological processes. The confined nature of the Great Lakes basins provide an environment which is logistically manageable and computationally efficient. Sophisticated instrumentation exists to adequately resolve the internal structure and variability of these features and remote sensing techniques provide a unique prospective from which the evolution of these fields can be viewed. Questions relating to food web dynamics and cross-shelf transport could be resolved by an integrated Great Lakes investigation of thermal fronts.

C. Upwelling and Stratified Conditions

Chairperson: Mark Donelan

Rapporteur: Everett Fee

1.0 Background

The stated goal of the Coastal Ocean Processes (CoOP) program is:

"to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of hiologically, chemically and geologically important matter on the continental margins [including the Great Lakes]."

The internal dynamics of lake systems are affected strongly by stratification. Furthermore, the local maximum in the density as a function of temperature gives unique properties to temperate zone fresh water bodies that have no counterparts in the coastal oceans. In particular, twice a year as the surface waters approach 4°C from above (in the fall) or below (in the spring) the water column becomes statically unstable and can mix from top to bottom. The consequences of this overturning are far reaching in the maintenance of the ecosystem and in the recycling of nutrients and contaminants.

During the strongly stratified summer season and the much more weakly stratified winter, the epilimnion is decoupled to some extent from the hypolimnion. Most of the primary biological productivity occurs in the strongly insulated epilimnion, whereas much of the nutrient supply is stored in the hypolimnion. For most of the year, the biological productivity in the relatively well-mixed epilimnion depends to some degree on the rate of mixing of nutrients across the thermocline. Other sources of nutrients are the atmosphere, through the air-water interface, and, particularly in the nearshore areas, fluvial advection and sediment-water fluxes. Variations in the wind stress produce adjustments in the stratification of the lake. Substantial tilts of the thermocline and consequent upwelling/downwelling in the coastal zones are believed to be important in the redistribution of nutrients and biota. Figure 1 (Irbe and Mills, 1976) shows the surface temperature structure of Lake Ontario on 23 May, 1972, as deduced from airborne infrared thermometry. The bunched contours at the 'thermal bar' separate the well-mixed interior of the lake from the strongly stratified coastal region. In Figure 2 (Simons and Schertzer, 1985) forty-eight hour averages of the temperature structure in a North-South section of Lake Ontario are shown in the spring and summer. By mid-July the thermal bar has collapsed and the thermocline is established across the lake, exhibiting upwelling on the north shore and strong downwelling on the south shore. (Boyce et al., 1989, provide a succinct overview of the thermal structure and circulation of large lakes).

2.0 Important/Guiding Questions

As this group saw it, the guiding question for a CoOP experimental plan to address is the following:

What are the dynamics and relative importance of recycling, turbulent mixing through the thermocline and upwelling as sources of nutrients to the mixed layer?

In addition, we felt that clarity would be well served by further breaking down the main question.

Sub-Questions:

Upwelling and Downwelling:

- Do nutrients from the upwelled hypolimnion locally alter the quality of biological production? e.g., (1) Si/P ratio could favor diatoms; (2) temperature changes may directly influence higher trophic levels.
- Do changes in zooplankton distributions affect higher trophic levels locally?
- Do upwelled currents ventilate and move sediments and nutrients?

Stratified Layers:

- Are temporary (e.g., diurnal) thermoclines biologically, geologically and chemically important? Or how rapid is bio-response versus physical relaxation?
- Is the structure and timing of stratification affected by biological matter-biofeedback?
- What are the spatial and temporal variabilities of the vertical eddy diffusivity (Kv) and how are they affected by storm events? (There are indications that Kv is largely determined by interaction with boundaries [Salmun et al., 1991]. Boundary mixing may well be dominant in enclosed water bodies such as the Great Lakes).

3.0 Approach

A full understanding of the dynamics and relative importance of recycling, turbulent mixing and upwelling as sources of nutrients to the mixed layer requires detailed measurements of the physical driving forces and the biological response.

Modern remote sensing methods, such high frequency radars can provide considerable detail of the large scale variability of coastal surface flows over a range of order 100 km, while ADCPs can obtain the structure of velocity components over a range of order 100 m. *In situ* laser and acoustic Doppler velocimeters are capable of resolving the fine structure of the velocities at a point. In recent years considerable developmental effort has gone into improving buoyancy-driven profiling devices for obtaining *in situ* data along a vertical transect and towed bodies capable of depth adjustment to obtain a quasi two-dimensional profile of *in situ* data along the ship's track.

In situ sensor technology has advanced at a commensurate pace and fast response, accurate *in situ* sensors are now available for velocity, temperature, conductivity, pH, oxygen, PAH, particles, transmittance, fluorescence, radiance and irradiance. Instruments such as the Fast Repetition Rate Fluorometer (Kolber et al., 1994) have been developed to yield rapid measurements of photosynthetic rate parameters.

Thus it is possible to design a coastal experiment with continuous monitoring of surface currents, temperatures and biological indicators (e.g., chlorophyll-a) over an area extensive enough to cover the large scales of such processes as upwelling/downwelling and coastal jets. At the same time, the appropriate placement of *in situ* sensors and profiling devices will yield details of the vertical structure. Frequent ship cruises will help to fill in the data from the moored arrays and will permit laboratory-quality measurements of parameters that are difficult to measure automatically.

3.1 Site Selection Criteria

Here we consider the choice of a suitable site that will allow a coherent approach to answering the guiding question. Areas of Lakes Ontario and Michigan are considered to have good upwelling/downwelling characteristics and are logistically more attractive than the upper lakes. Lake Erie's special nature excludes it from a general study of common lake phenomena. We recommend consideration of sites along the western and eastern shores of Lake Michigan and the south shore of Lake Ontario. Strong upwelling/downwelling events have been documented in these areas and, in addition, both lakes are well served by large limnological laboratories.

3.2 Planned Observations/Data

Moored arrays and continuous remote sensing systems (shore-based radar, blimps) should be put in place by the end of April and operated continuously to the end of October. Where possible ship cruises should be conditioned on the observations from the remote sensors coupled with numerical modelling of the relevant phenomena.

The moored arrays should provide high resolution temporal and vertical sampling of important physical and temporal parameters. Horizontal resolution will necessarily be lower, but at least three stations will be required to yield useful information on the advective terms. Vertical resolution should be higher in the epilimnion than the hypolimnion and highest in the boundary regions (thermocline and the top and bottom interfacial regions). Special care should be given to estimating fluxes at the top (air-water interface) and bottom (sediment-water interface).

3.3 Modeling Needs

Ohio State University and GLERL (Schwab & Bedford, 1994) have advanced the art of physical modelling on the Great Lakes to the point where it can be used both as a tool for experimental planning and day-to-day forecasting, and for interpreting the data. These models should be an integral part of the experimental plan from the outset. As far as possible, biological and chemical constituents should be included in the models.

3.4 & 3.5 Instrumentation Needs and Sampling Platforms

The observational network will include all the following components: moored arrays; ship surveys; remote sensing from aircraft and satellites; remote sensing from blimps (longer term than from aircraft and satellites); and HF shore based radar for surface currents.

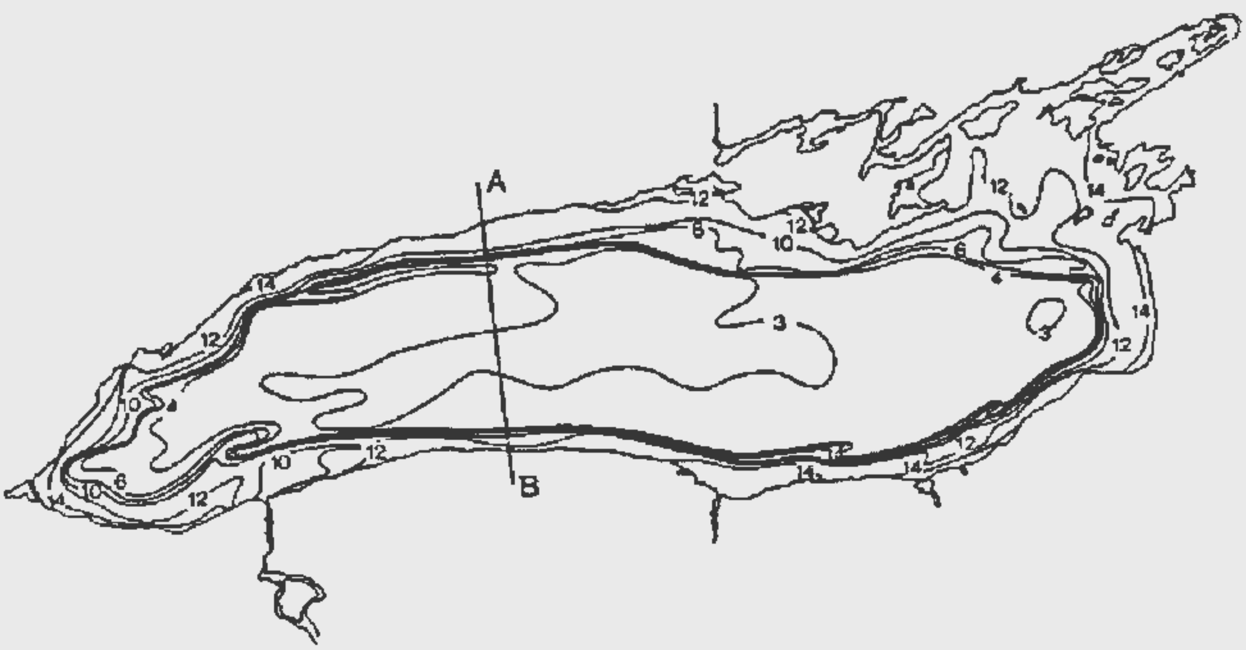


FIGURE 1. Surface temperature map of Lake Ontario for 23 May 1972, made with an airborne infrared thermometer (Irbe and Mills, 1976).

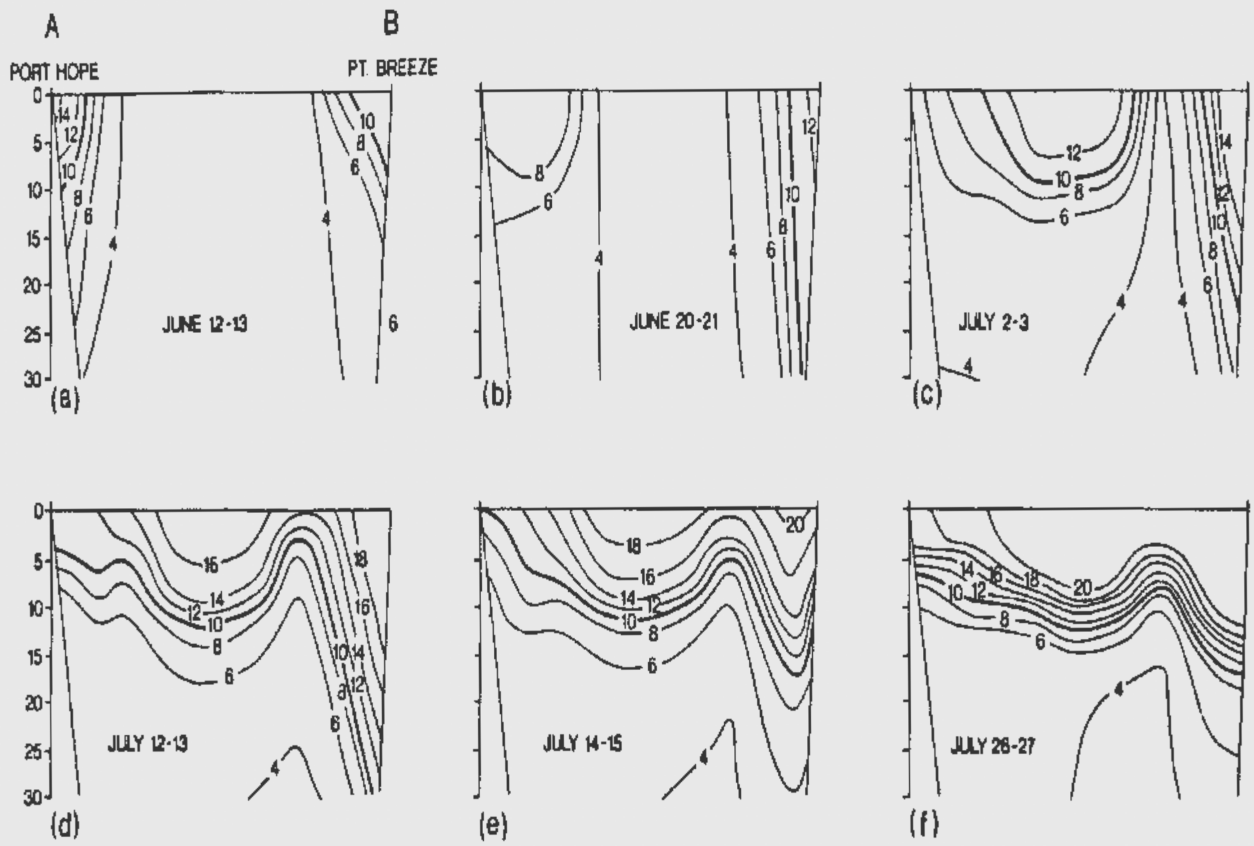


FIGURE 2. Distribution of temperature on a cross-section of Lake Ontario from Port Hope, Ontario (A), to Point Breeze, New York (B). (Simons and Schertzer, 1985). The location of the section is indicated in Figure 1. The cross-sections are assembled from time series data collected at the mooring locations; each section represents a 48-hour average.

D. Physical Dynamics of Coastal Systems and their Relationship Among Biological, Chemical and Geological Components

Chairperson: Keith Bedford

Rapporteur: Gary Fahnenstiel

1.0 Background

The Great Lakes CoOP seeks to define a process study that will obtain a new level of quantitative understanding of the processes that dominate the transports, transformation and fates of biologically, geologically and chemically important matter. This goal should be pursued within the context of the National CoOP program objectives, which are to understand:

> **The quantitative mechanisms, rates and consequences of cross-margin transport of momentum, energy, solutes, particulates and organisms; the atmospheric and air-sea interaction processes that affect biological productivity, chemical transformations, and cross-margin solute and particulate transport; the roles of transport processes that couple the benthic and pelagic zones of the continental margin; the nature, effects and fates of terrestrial inputs of solutes, particles, and productivity in the coastal ocean; and the transformations of solutes, particulates, and organisms across the continental margin.**

As requested by the workshop organizers, working group reports such as this should concentrate on the following series of questions.

1. **What are the important CoOP-specific scientific problems to be addressed and why are they important?**
2. **How should these problems be addressed in a cohesive interdisciplinary manner?**
3. **What are the motivations or rationales for recommendations on:**
    - geographic locations and planned observations?
    - required modeling and field work?
    - data needs?
    - instrumentation needs?
    - vessel and facilities needs?
    - cooperation with other programs?

4. What are the highest priority questions and approaches?

5. What are the societal implications and benefits of the study?

2.0 Important/Guiding Questions and 3.0 Approach

The Concept of an Episode

The attempt is made here to first define and categorize the various kinds of episodes and then proceed ahead to address the report questions outlined above. The information accumulated in this workshop report is based upon a number of existing review documents, several of which already address episodes and the interactions between biological, chemical and physical responses. These include the workshop journal articles by Boyce et al. (1989), Mortimer (1988), Rea et al. (1981), and Robbins and Eadie (1991). Several recent workshop reports have already defined most of the issues to be summarized here, chief amongst these is the NOAA-GLERL/CILER *Great Lakes-Coastal Ocean Program Workshop* (1992), and Smith and Brink (1994). Earlier and still highly relevant workshop reports include the NSF/University of Michigan report on *Basic Issues in Great Lakes Research* (1987), and Brink et al. (1992). All these reports are detailed and well referenced and this report will not reproduce for a sixth time the information in these reports.

The explicit experimental focus on episodes and the resulting biological and chemical reorganization they unleash in the Lakes was first recommended in the 1992 GLERL/CILER report. We begin this report with an attempt to categorize the various episodes discussed in the GLERL/CILER report and in our working group. This, in itself, proved most challenging because with most scale and process-dependent activity, one scientist's forcing episode might be another's response function. If a nearshore control volume is assumed, with land as the shoreward boundary, then six interfaces take place by which flux exchange occurs with the internal control volume (Figure 1). One possible organizational distinction between processes is based upon whether the episode is physical, chemical or biological in nature. But perhaps the most fundamental distinction becomes whether the episode represents the effect of an agent external to the control volume which results in an internal response or reorganization in the control volume. This internal reorganization may ultimately result in a re-transfer or flux out of the control volume.

Ones natural inclination is to automatically think of storms as the prototypical physical episode. They are intensive, contain high spatial and temporal gradients, and are probabilistic in their occurrence frequency, magnitude, and trajectory. Yet, other repetitive physical processes occur in the Lakes which are equally important but not quite so random in their overall occurrence. Therefore, the definition of episode must be based upon the degree of disruption it causes within the nearshore zone. Table 1 is an attempt to list all the physically based "episodes" whose imposition on a control volume boundary results in an internal reorganization in the nearshore control volume. The time bases for these disruptions are fairly well known. Storms occur approximately every 5-7 days in the fall, winter, and spring and every 7-10 days in summer. The transient nature of the storm path results in substantial backing or veering of the wind direction over periods less than a day, accompanied by often dramatic increases and decreases of wind speed over the event cycle. Wind fields can result in storm surges which cause both temporary flooding and draw-down. Intense rain also results in temporary flooding and corresponding high tributary discharge, especially the discharge associated with spring runoff. In summary, there is no persistent wind speed or direction, even over periods of a day. Only patterns of speed build-up, decay, and propagation direction are persistent.

On an annual basis, the seasonal heating, cooling, and ice formation stages have a profound impact on the biology and chemistry of the Lake. As noted in the references, the spring/summer portion of the heating cycle takes six months to achieve maximum heat content and stratification. In the fall, convection-aided overturning during cooling allows the heat to escape rapidly over a period of approximately four months. As noted in Assel et al., 1983, the ice season depends on whether the Lake is southern (Erie) or northern (Superior), but in general is two to three months long. The impact of the ice period on the biology and chemistry is largely undocumented.

Drought cycles occur over periods of decades and are not at all well documented in terms of climatology or impact. The antithesis of droughts is floods, or more appropriately, high water levels, and these also have decade time bases. Typically, both extreme events occur as a result of sustained changes in the formation and propagation characteristics of precipitation-bearing storms (rain or snow). Both result in fairly large changes in mean annual water level, which persist for a matter of one to three years.

In Table 1 there are three fairly important episodic boundary loading events (storms, ice and tributary runoff), which appear to have a strong influence on the resulting annual limnological (physical, chemical, and biological) cycle. As our group discussion proceeded, it was clear that we could decide no further as to which is the most important episodic feature to recommend for study as there was insufficient scientific evidence upon which to base our decision; therein lies the origin of our first recommended CoOP scientific question.

Internal to the control volume, a variety of physical, chemical and biological responses occur as a result of the boundary loadings. These responses are also episodic and possess sharp temporal and spatial gradients as well as intense magnitudes. A list of the processes comprising the motion and associated transport is in Tables 2 and 3. This list is daunting and again raises the issue of what "episodic" should refer to and what focus this report should have.

In attempting to resolve the issue of whether episodes include not only the forcings but the internal responses, it is noted that the remaining work groups are, in fact, already reporting upon the important episodic responses within the control volume, including: coastal jets and long shore processes; thermal fronts (including vernal dynamics and structure); and, upwelling and stratified conditions. In order to focus this report, it was therefore decided that episodes shall refer to the nature of the boundary loadings, not the internal process responses. The remainder of this report adopts this perspective.

Wind-driven transport and tributary flows are ubiquitous coastal features and the question still remains as to how Great Lakes episodes might be defined, or unique, relative to other coastal situations.

Episodic Versus Persistent Forcing: The West Coast Contrast

Our CoOP Great Lakes workshop document will focus on almost the identical issues as those considered in this West Coast cross-shore transport processes study (Smith and Brink, 1994). Many, if not most, of the references would capably apply in support of the hypotheses and rationales being offered for the Great Lakes study. Indeed, much of the burden of detailed literature review can, for a number of the Great Lakes CoOP work group reports, be reduced by simple reference to the West Coast report. The question for the Great Lakes CoOP reports then becomes quite pointed, i.e., if the similarity of the cross-shore transport study is so complete, down to the focus on the wind-driven nature of the forcing, then what sets the proposed Great Lakes CoOP study apart from theirs? Or, how may the Great Lakes study elaborate or add to the insight gained in their study?

This report's position is that in addition to the obvious fresh versus saline water difference, three significant differences arise. The first difference lies in the recirculating nature of the Great Lakes flow field. Here, wind-driven circulation can aid in cross-shore transport but instead of permanent loss to the offshore, as in the ocean, material can be returned to the nearshore zone, often over time periods as small as days. Secondly, the ratio of the shoreline length to Lake volume is quite large (except for Lake Superior) in contrast to the ocean and, therefore, the boundary loadings will have a much greater impact on the equilibrium distributions of material throughout the lake volume. The third difference lies in the episodic, intermittent, transient nature of the boundary forcings summarized here.

It is noted that the West Coast experiment does focus on wind-driven cross-shore transport but that there is seasonal persistence in the general northward or southward wind forcing and corresponding upwelling or downwelling. The forced response (upwelling or downwelling) lasts for quite sometime, being time-modulated by tidal activity. With the West Coast shelf control volume being so large, river volume inflow is of little consequence and therefore so is storm-induced precipitation inflow. Ice cover and the resulting period of calm each year is nonexistent. The benefits of such persistence also extend into a much less temporally variable heating and cooling cycle at the West Coast site. Certainly, daily and seasonal cycles exist, but they are confined to a relatively thin region of the large coastal shelf control volume.

The persistence of the forcing, coupled with the significantly larger West Coast control volume of scientific concern, results in an experiment where the dominant processes to be measured separate out in time and space and allow direct high quality correlation with just one dominant persistent forcing: wind.

In contrast, the episodic nature of the Great Lakes forcing functions (and associated responses) results in the following attributes which could form the basis for a contrasting Great Lakes nearshore transport study.

1. The 7-10 day storm time base results in wind-driven circulation whose baroclinic motions are short lived and whose barotropic motions contain rapid longshore current flow reversals over fractions of a day.
2. The wind-driven spin up and set down cycle of the Lake circulation field can be completed in a matter of several days, with inter-event periods containing mostly wind waves and weak hydraulic throughput.
3. The cooling periods occurring during storms can result in significant convective cooling and destabilization, especially during the early seasonal warming stages and the fall cooling cycle. These cooling events cause strong vertical transport which, unlike the West Coast setting, penetrates the full depth of the water column in the nearshore control volume.
4. The ice season suppresses episodic wind-driven transport and allows persistent chronic but low intensity transport and transformation processes to be effective without the extreme perturbations exhibited during storms.
5. With watershed area and runoff yields being comparable to the ocean coast, but with Great Lakes nearshore control volumes being a good deal smaller, it is expected that tributary plumes will be a much more important agent in cross-shore shore transport than in the West Coast.

6. With the depths of the nearshore control volumes being comparatively smaller than the West Coast (at least for Lakes Ontario, Erie, Michigan and Huron), but with fetches typical of ocean storm fetches, surface wind waves will be a much more fundamental transport agent over the control volume, especially as regards sediment remobilization.

7. Though not a direct product of an episodic forcing climate, the closed nature of the basin, combined with direction reversing flows and wind-driven whole basin circulation, suggests the significant possibility of continuously recycling material in and out of the nearshore control volume during the limnological year.

With there being such a probabilistic/stochastic nature to the episodic system, the question of how to compose a science experiment becomes increasingly complex. Ideally, one could elect over the projected course of the two years, to concentrate on field measurements that measure in detail the forcing functions, control volume responses, and resulting cross-shore and longshore fluxes. This, once again, would be in direct analogy to the West Coast science program. It is unlikely that a two-year field experiment alone would suffice in creating the full extent of the correlations. It most certainly however would elaborate on the mechanisms at work in each individual episode.

The episodic nature, plus the smaller size of the lakes, suggests a second component of a contrasting Great Lakes study. Here, we propose that robust 3D models of the Lake and nearshore processes be employed to perform simulations of statistically expected episode conditions. These models would be validated and improved based upon the field data collected during the CoOP experiment and then used in a simulation mode to synthesize conditions not captured in the two year snapshot of data. These simulation results could then be used to complete the correlations between cross-shore transport and boundary loading conditions as well as test various hypothesis about the significance of the various episodes and their loading patterns during the limnological year. Such models are in use at this time and are usable on a number of Unix-based workstations. Therefore, it is expected that a considerable number of simulations could be economically performed.

The remainder of this report concentrates on rationalizing and configuring a science program consisting of a balanced field work and modeling experiment. Unlike the other group reports comprising this appendix, this summary *does not* concentrate on one or two processes for scientific elaboration. Rather, this document suggests a viewpoint for analysis which could be applied to any of the nearshore processes to be studied.

With regard to the questions asked of the report and reporters by the Organizing Committee, the following information is offered.

The CoOP Specific Objectives (Planning Question 1)

The Great Lakes CoOP seeks to define a process, model and simulation study that will obtain a new quantitative understanding of the effect that episodic storms, ice, and river/tributary inflows have on the processes that dominate the cross-shore transport, transformation and fate of biologically, geologically and chemically important matter. This program is pursued within the context of the full CoOP program objectives stated previously. The following series of questions form the set of science objectives or hypotheses to be addressed.

1. Are wind events, tributary runoff, or ice breakup initial conditions the dominant agent in the resulting cross-shore distributions observed during the subsequent limnological year?

2. In any one limnological year, will a single large annual event dominate the resulting cross-shore transports, transformation and fates, or will the chronic year-long cycle of episodic storms be the dominant influence?

3. Are the spatial and temporal patterns of the boundary episodes a stronger determinant of cross-shore transports, transformation and fates as opposed to the intensity of the events?

4. Will the pattern and intensity of the episodes result in fundamentally different biological, geological and chemical materials being transported offshore in any one limnological year?

5. Will the pattern and intensity of nearshore recirculation (or recycling) resulting from whole basin wind-driven circulation affect the type and character of the biologically, geologically and chemically important materials being transported offshore during any one limnological year?

Due to the blend of simulation and field work, there is one further question about model structure can be addressed with this experiment.

6. Is all this highly detailed spatial and temporal resolution and corresponding complex hydrodynamics necessary to improve the management level water quality models used to make planning decisions as based upon monthly and yearly average conditions?

In attempting to offer a rationale for this series of questions (objectives), it is perhaps most useful to start with the last question (objective) and go backwards. The Great Lakes has been a hotbed of first-time computer-model developments, as motivated by the Canadian-U.S. Great Lakes agreements to manage Great Lakes environmental issues. So it was with management-based water quality models. Until recently, typical water quality models were of the box mass balance variety, where the Lake is broken into large boxes (10 km or greater) and chemical reactions and boundary exchanges across the boundary faces occurred. Typical time and space steps were those required to address management questions such as, What are the annual or monthly pollutant loadings and associated fates? Until now, the only hydrodynamic information included highly averaged (weekly, monthly) steady flows. Mixing coefficients were used for occasional adjustments.

We have steadily been increasing the resolution of these models as computers get larger and our information requirements become more sophisticated. Spatial and temporal scales of the water quality processes in the models are now at the size where they are consistent with hydrodynamic processes and, as our nearshore study here indicates, the interactions between water quality and hydrodynamics are assumed to be multiple, nonlinear, and broadband. Yet the fact remains that the information needs of basin water quality managers and planners still require planning information at the relatively long month and annual periods. Therefore, the question arises as to whether explicit consideration of the high resolution processes in the water quality management models will substantially improve the monthly and annual average outcomes used by the planners. After this study, it is assumed that the science of nearshore transport processes will be quite improved but we must also be able to say whether or not our management tools and corresponding predictions will improve. The increased cost of going to an episodic/probabilistic basis for management models must therefore be assessed as regards the improvement in predicted data.

With this rationale in mind, the first five objectives form the scientific bases necessary to create a new knowledge base on offshore transport phenomena as well as pursue the question of possible improved management predictions and scenario examination. Question (1) examines the relative impact of the three primary episodes amongst each other while questions (2) and (3) address the relative importance of the events being in a particular sequence or time series (2) and the intensity of the events (3) in determining the observed offshore transport. Two scales of experimental and modeling interest occur here: What are the transport, transformation and fate processes occurring in each episode comprising the year-long cycle?; and what are the integrated (monthly, annual) average values for the metrics being sampled and/or modeled?

The question of the role of ice is particularly intriguing because very few studies have been performed to assess its role in forming the initial condition for the ice-free limnological year. Claims have been made in various forms that the character of the ice season is the single greatest determinant of the subsequent ice-free year-long cross-shore transport. In other words, the annual offshore flux is most determined by the initial condition. Some have speculated that the biggest wind storm of the year is the greatest determinant, while others have speculated that the winter melt runoff is the single most important variant. In fact, this last assertion was the focus of a large U.S.-Canadian study (called PLUARG, 1978-1982) which was based on tributary plume experiments marked by the complete absence of any hydrodynamic measurements at all.

As opposed to this big-bang theory of nearshore processes, the nearshore exposure to chronic year-long patterns and intensities of episodes is often suggested as a dominant correlate to internal transformation and offshore fluxes (questions (3),(4),(5)). The timing and distribution of storms relative to anthropogenic inputs such as Spring insecticide/pesticide applications or airborne pollutant inputs has been asserted to be a major factor in the timing and character of nutrients delivered to the nearshore zone. This suggestion has been extended to include the possibility of episode patterns, therefore determining the resulting phytoplankton community structure. The impact of nutrient nearshore recycling patterns resulting from whole-basin circulation further confounds the resulting observations.

Answering questions (1)-(5) then yield scientific insight as to the role and the importance of episodes in nearshore transports, transformation and fates, and provides data to answer the question as to whether such high resolution precision helps or detracts from improving long-term planning. The scientific plan offered in the rest of this document is therefore not so much a plan but a suggestion for a way of thinking about how to use the data once the field experiment is completed. The basis for this comment is that the field data requirements are probably similar to the recommended West Coast experiment and the suggestion from the other work groups in the Great Lakes CoOP; i.e., a very intensive field program designed to provide long-term time series (two years) of nearshore observations with embedded high spatial resolution Eulerian and Lagrangian sampling of each episode forcing and response attributes. Our recommendation concerns the question of how to use and analyze the data that are collected.

Interdisciplinary Study Basis (Planning Question 2)

The basis for the study plan is that it would be fully interdisciplinary in nature with equal hydrodynamic, biological, and chemistry partnerships. The probabilistic nature of the science plan recommendation reinforces this requirement.

Motivation and Rationales (Planning Question 3)

3.1 Site Selection Criteria

In order to separate out the various forcing effects, some possible experiment regions come to mind. First, Lakes Erie, Ontario, and Michigan are the most extensively studied of the five Lakes; Michigan by the U.S. and NOAA laboratory scientists and Ontario by the Canadians, occasionally assisted by U.S. scientists. Both Michigan and Ontario have good thermal signatures and opposing dominant fetches (Michigan, north-south; Ontario, east-west). Erie is the shallowest, has the shortest residence time (two years), and responds quickly and vigorously to storms. All three will be part of the Great Lakes Forecasting System (GLFS) operational prediction stream by the end of summer 1995. All three ice over, and all three have one or two excellent tributaries with typical agricultural and urban land use patterns. Saginaw Bay and Green Bay are not considered to be good candidates for study as they are anomalous in shape, volume, modal coupling, and geometry. Results from experiments in these sites have not been at all transferable to any other setting in the Lakes to date.

3.2 Planned Observations/Data

The field work concept is outlined above and is essentially an interdisciplinary nearshore embedded study. The chief decision required to proceed is as follows: in addition to the hydrodynamic and thermal data on both the forcing episodes and internal physical responses, what biologically, geologically and chemically significant parameters of importance are to be correlated with the physical episode disruptions? Here, the working group listed a number of possibilities but could not focus in on one or two-or a suite-of metrics to sample. Suggestions included:

- nutrient availability associated with particles;
- redox/sediment water interactions;
- particle associated contaminates and recycling;
- major ion inputs and loses;
- habitat disturbance, diversity and recruitment;
- biodiversity;
- larval distrihution displacement;
- biodiversity;
- larval prey availability;
- primary and secondary productivity
- pathogen distributions;
- bioturbation.

It should he the overall goal of the field program to sample throughout the entire year, including the ice season. It is realized that ice season sampling is a precarious undertaking, therefore the recommendation is to sample as completely as possible at the beginning and end of the season and maintain, if possible, baseline time series data obtained with permanently moored instruments.

During open field conditions a fairly traditional set of measurements and associated systems is recommended for the physical, biological, and chemical variables, including:

- permanent moored Eulerian time series measurements at fixed strategic sites;
- Lagrangian/particle/parcel tracking experiments during episodes;
- remote sensing and surface mapping by operational satellites and flyovers of opportunity;
- fixed tower observations for air/sea exchange experiments;
- adaptive, phenomena and process experiments employing the Great Lakes Forecasting System in real time shipboard operation;
- laboratory based reaction studies of *in-situ* samples;
- submersible mobile mapping of spatial bathymetry and bottom sediment characteristics.

It is important that the spatial density of the instrumentation be sufficient to fully resolve the spatial data required to calculate the fluxes and integrated mass quantities on control surfaces 1, 2, and 3. These data need to be collected at high frequencies in order to resolve the turbulent diffusion contribution of the flux and have enough vertical resolution to comprehend the variability introduced by any vertical thermal stratification.

3.3 Modeling Needs

Before proceeding ahead to do many simulations, a climatological summary of historical meteorological and hydrodynamic data should be accomplished. The existing storm data base held by P. Samson at the University of Michigan is an excellent starting place. In this fashion, the annual storm tracks and intensities can be analyzed for frequency of occurrence, and methods of sequence analysis and pattern recognition can be applied to determine which annual cycle of storms and associated characteristics are dominant and frequently observed. Such a procedure has already been applied to a 20-year hindcast of nearshore Cleveland longshore and cross-shore Lake Erie behavior for a combined sewer overflow (CSO) study.

By having the storm patterns analyzed and classified, the two-year suite of measured episodes can be classified as frequently observed or anomalous in pattern and intensity, and therefore, in that light, assess the correlations examined in the scientific questions.

After the extension of GLFS to include appropriate biological, geological and chemical constituents and verification with the two-year field data, the tools exist by which to use simulation theory to extrapolate the correlations developed in the field data years to include all the expected forcing function patterns observed in the existing climatology data base.

For possible episodic conditions not spanned in the record, synthesized forcing patterns can be attempted and used to perform scenario or "what if" types of model interrogation. As noted earlier, this entire modeling sequence is an elaboration of a probabilistic analysis already developed for, and applied to, CSO remediation planning for the City of Cleveland and, therefore, much of the modeling work required for its implementation already exists for Lake Erie.

3.4 Instrumentation Needs

Beyond the needs discussed in the GLERL/CILER report and the CoOP West Coast experiment, the remaining instrument and data needs this episode-based project requires includes new non-destructive/non-invasive, rapid-response in-situ instruments for grain size measurement. Further instrument development is required for non-invasive characterization of the bottom, such as the micro vertical distributions of grain size and pore water concentration. The liberal use of vertical profiling acoustic Doppler current meters (both long and short range) will be required along faces 1, 2, and 3 for doing the flux analysis.

3.5 Sampling Platforms

One well equipped oceanographic vessel prepared for year-round operation is required, as are close-proximity shore facilities for real-time instrument readout and receipt of GLFS forecasts.

3.6 Cooperation with Other Programs

Cooperative, leveraged research will be strongly pursued. Potential collaborators include USGS, USEPA, NOAA-Sea Grant, NOAA-GLERL, CCIW, NWRI and the Canadian Ministry of the Environment.

4.0 Summary

Recognizing the scientific and management nature of the program, the two most fundamental questions to be addressed are questions (1) and (6). Questions (4) and (5) are of almost equal importance, as they must be addressed in order to fully answer question (1).

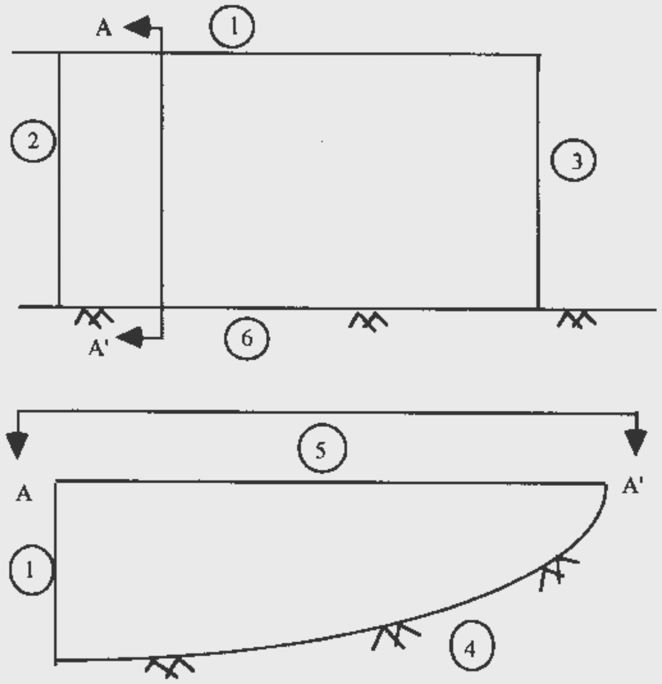


FIGURE 1. Nearshore control volume and boundary enumeration.

TABLE 1. Physical forcing episodes

Class	Components	Natural/ Anthropogenic	Boundary Loadings	Location (Face # Fig. 1)
I. Storms	a. wind	N	1. windshear	5
			2. waves	5
			3. currents	1, 2, 3
			4. water level-surges, short term	5, 6
	b. rain (see also IIe)	N	5. water level - long term	5, 6
			6. floods	5, 6
			7. tributary inflows	6
	c. snow (see also IIe)	N		
II. Annual Heating/ Cooling Cycle	a. heating cycle	N	8. surface heat flux	5
	b. cooling cycle	N	9. surface heat flux	5
	c. ice formation	N		5
	d. ice breakup	N		1, 2, 3, 6
	e. spring runoff	N	10. mass/momentum flux	internal
III. Droughts/ Floods		N		internal

TABLE 2. Summary of Great Lakes hydrodynamic processes and scales.
(Boyce, 1974; Bedford and Abdelrhman, 1987)

A partial list of motions and their associated time and space scales. Letters in parentheses refer to the nature of the scale used. The governing terms in the equations of motion and continuity are listed in column 6 according to the key below.

(1) Phenomenon	(2) Length Scale Horizontal	(3) Vertical	(4) Time Scale	(5) Vel. Scale	(6) Dynamics Major Components
a. Wind driven surface gravitational waves	10 m(S)	1 m(M)	1s(P)	10 m/s(C)	1,2,6,10
b. Surface gravitational waves-seiches	100 km(S)	10 cm(M)	2-10 h(P)	2 cm/s(H)	1,6,9,10
c. Short freely propagating internal waves	100 m(S)	2 m(M)	5 min(P)	2 cm/s(H)	11,2,7,10
d. Long propagating internal waves	10 km(S)	2 m(M)	1 day(T)	50 cm/s(C)	1,5,7,9,10
e. Internal gravitational standing waves or seiches	10 km(S)	2 m(M)	15 h(P)	10 cm/s(H)	1,5,7,10
f. Surface wind drift	--	10 cm(S)	-	2 cm/s(H)	10,12
g. Coastal currents	10 km(S)	-	1 day(T)	10 cm/s(H)	all
h. Upwelling and downwelling	10 km(S)	10 m(M)	1 day(T)	<1cm/s(V)	all
i. Wind driven horizontal circulation	100 km(S)	100 m(S)	1 day(T)	10 cm/s(H)	all
j. Geostrophic current	--	--	1 day(T)	3 cm/s(H)	5,6
k. Langmuir circulations vertical mixing of epilimnion	--	10 m(S)	1 h(T)	1 cm/s(V)	1,2,3,4,10,12, 14, and others
l. Tides					
a) diurnal	Earth radius	--	1 day(T)	--	1,2,5,15
b) semidurnal	Earth radius		1/2 day(T)	--	1,2,5,15

M amplitude of motion;
S distance over which phenomenon varies significantly;
P period;
T time interval over which phenomenon varies significantly;
C wave speed;
V vertical particle velocity;
H horizontal particle velocity.

\- - - - - - - - - - - - -

1 time-dependent horizontal accelerations;
2 time-dependent vertical accelerations;
3 advective component of horizontal acceleration;
4 advective component of vertical acceleration;
5 Coriolis force;
6 pressure gradient force due to slope of free surface;
7 pressure gradient force due to slope of the thermocline;
8 pressure gradient force due to atmospheric pressure field; variations in bottom topography;
9 wind energy/stress;
10 internal stresses arising from horizontal current shear;
11 internal stresses arising from vertical current shear;
12 friction against boundaries;
13 potential energy changes due to surface heating/cooling;
14 astronomical tidal-generating forces due to sun-earth-moon gravitational potential field;
15 potential energy changes due to temperature, salinity and sediment changes.

TABLE 3. Summary of Great Lakes transport processes and scales.
(reference Table 2 for the key)

Phenomenas	Horizontal	Vertical	Time Scale	Dynamics of Components
n. thermocline formation		10-50m (S)	1 month	10, 12, 14, 16
o. thermocline decay		10-50m (S)	1 month	10, 12,, 14, 17
p. thermal bar/front	2-3 km (S)	10-50m (S)	1 day (T)	1-14, 16
q. spring/fall overturn	10-1000m (S)	10-100m (S)	2 weeks (T)	17, 14, 16, 2, 10, 11, 12
r. tributary plume dispersion/diffusion	10-1000m (S)	5-20m (S)	1 day (T)	3, 9, 10-13, 14, 16
s. sediment entrainment	1-100m (S)	1-5m (S)	1 hour (T)	10-12, 13
t. sediment deposition	1-100m (S)	10-100m (S)	1 day (T)	18, 11, 12
u. shoreface/beach erosion	10m-1km (S)	--	1 hour (T)	1, 2, 6, 10
v. offshore ejection	10-1000m (S)	10-50m (S)	1 day (T)	1-14, 16
w. turbulent diffusion of heat or mass	10m-1km (S)	--	1 hour (T)	1, 2, 6, 10

E. Benthic-Pelagic Coupling in the Great Lakes: Implications for Hydrological, Solute, Sediment and Biotic Interactions

Chairperson: Hans Paerl

Rapporteurs: Susan Henrichs, Mark Wimbush

1.0 Background

Water, solute, gas and particle exchange in the Great Lakes are associated closely with and controlled by spatial and temporal coupling of the water column and benthos. Nutrient cycling, biological production and trophodynamics are in large part a product of the rates and magnitudes (i.e., mass flux) of benthic-pelagic exchange. Specific production and trophodynamic characteristics perceived to be "problematic" from water quality, ecosystem and human health perspectives (e.g. hypoxia/anoxia, trophic shifts, eutrophication and algal blooms) are intimately linked to either naturally- or anthropogenically-induced alterations in the benthic-pelagic interplay, or coupling, of physical, chemical and biotic processes. It follows that clarification of physical and chemical controls of Great Lakes material cycling and exchange, production and trophic states is reliant on a clear conceptual and mechanistic understanding of benthic-pelagic coupling.

In the following sections, we summarize key physical, chemical and biotic controls on and ramifications of benthic-pelagic coupling as they pertain to aspects of material transport, cycling and production in the Laurentian Great Lakes. This report is not intended to cover all aspects of physical, chemical or biological processes relevant to CoOP's mission. Rather, it should serve as a framework for placing benthic-pelagic coupling in appropriate perspective and focus with regard to cross-shelf material transport, cycling and assimilatory processes of central importance to Great Lakes physical, chemical and trophodynamics.

Nearshore Circulation and Sediment Dynamics: Their Impacts on Benthic-Pelagic Coupling

Nearshore circulation has been more thoroughly addressed in the "Coastal Currents and Coastal Jets" workshop report (see Appendix 2.A.). Specific features of nearshore circulation will be considered here on the basis of their interactions with and impacts on benthic-pelagic coupling. Nearshore flow in the Great Lakes is typically concentrated in a narrow "coastal jet". Flow in this jet is parallel to shore and often swift. Because of this, the large eddy structure in the turbulent benthic boundary layer (BBL) of such a coastal jet can have an organized structure in the form of longitudinal counter-rotating vortices, and the underlying bed can have associated cross-stream variation in its properties. For example, there is a region of sediment furrows at approximately 100 m depth under the Keweenaw Current in Lake Superior. These furrows are parallel to the predominant flow direction, and are spaced 20-100 m apart. It has been shown (Viekman et al., 1992) that there is a flow convergence just above the furrows and divergence 7 m higher in the water column, which suggests the existence of counter rotating vortex rolls in the BBL, with resulting upward flow just above the furrows. Sediment in the furrow has a higher fraction of sand and coarse debris than in the area between the furrows. This type of flow-sediment interaction and resulting in homogeneity will significantly affect benthic-pelagic couplings and sampling strategies designed to investigate them.

Although the large-scale circulation patterns of the Great Lakes are reasonably well understood (see review by Boyce et al., 1989), certain aspects of sediment transport associated with hydrodynamics are less well known. The long-term effects of sediment transport and sorting have been characterized (Edgington and Robbins, 1990). However, what remains unknown are the processes involved. In their review of sedimentary process in the Great Lakes, Rea et al. (1981), convey very little about the transport paths of fine-grained material. Since many important contaminants and nutrients in the lakes are transported in association with fine-grained material, knowledge of the transport paths of this material, and in particular the details of its exchange with the lake bottom (sediment resuspension and deposition), are required for a better understanding of the ecosystem as a whole. Numerous experimenters have conducted studies of the cycling of various chemicals (for instance Robhins and Eadie, 1991; Baker and Eisenreich, 1989; Eadie et al., 1984), but few of these studies have examined the actual mechanisms involved in this exchange.

A substantial amount of knowledge exists concerning accumulation of sediments, especially in Lakes Michigan and Erie. The mechanisms and processes controlling rates, and directions (i.e., vertical vs. horizontal) of particle movement from source to sink are far less clearly known. We know that horizontal movement occurs on time scales up to decades (Edgington and Robbins, 1990), but how particles move has not heen studied. We suspect that particles move in "skips and jumps", driven by wind events that simultaneously resuspend material and transport it down-current. Wind forcing is short-lived in the Great Lakes, i.e., wind events sufficient to disturb nearshore conditions occur on ca. every 5 to 7 days during the winter, spring and fall and ca. every 7-10 days in summer. These are short-term events, generally <1 day. Is this the principal driving force for particle transport, or are less frequent, more intense events key determinants of particle movement? Lastly, the interaction of the bottom with the water column as well as thermal bar dynamics must undergo significant shifts during this transition.

Material exchanges and mixing near the sediment-water interface are clearly involved in benthic-pelagic coupling in the lakes. For instance, Edgington (1994), has examined the effect of benthic-pelagic coupling on the long-term behavior of plutonium in Lake Michigan and demonstrated the importance of the mixed layer on controlling water column concentrations. Chambers and Eadie (1981), documented the existence of a benthic nepheloid layer (BNL) in Lake Michigan throughout the stratified period. Because of its location just above the bottom, this layer is thought to mediate the exchange of material between the lake bottom and the open water above. Since then, BNL have been found in all of the lakes, and several sediment trap studies have been done on the relationship between resuspension and the BNL (Rosa, 1985; Sandilands and Mudroch, 1983). Other investigations have focused on the distribution of the BNL (Halfman and Johnson, 1989) or the chemistry of the material within it (Olivarez et al., 1989), but only a few studies have made time-series measurements of the physical processes actually involved in resuspending and depositing fine-grained material in the open lake. Lesht and Hawley (1987), reported that material on the lake shelf (30 m) was resuspended by wave action associated with fall storms, and by the movement of the thermocline past the site, but Hawley and Lesht (1995), reported that in four months of observations they observed no resuspension at depths below wave base. Thus, there is considerable uncertainty as to under what conditions material exchange between the lake bottom and the overlying water column actually occurs in many parts of the lakes.

In a broader context, resuspension and deposition of bottom sediments and pore waters also have been shown to affect benthic-pelagic coupling in other environments than the Great Lakes and through other pathways than those described above. For example, resuspension has been shown to control rates of organic carbon remineralization in the Georgia Bight (Hopkinson, 1985), and (theoretically) to delay the burial of fresh particulate material (Sanford, 1992). Sediment/pore water resuspension also has been implicated as an important mechanism for nutrient recycling in the Gulf of Mexico (Fanning et al., 1982), and the Kattegat (Floderus and Hakanson, 1989), though simulation of storm induced resuspension in estuarine mesocosms (Oviatt et al., 1981), showed a nutrient pulse associated with the storm event but little long term effect. The importance of resuspension for biological processes has also been demonstrated (Rhoads et al., 1975; Tenore, 1977; Taghon et al., 1980; Wainwright, 1987 and 1990; Ritzrau and Graf, 1992). In many of these cases, however, the effects of resuspension have been inferred after the fact, or the potential influences of resuspension have been estimated but not directly demonstrated. Relatively few studies have directly addressed the mechanisms linking physical resuspension and deposition processes with their biological and biological, geological and chemical consequences.

Trophic Interactions and Shifts

System productivity and trophic interactions exhibit strong seasonality and are dependent on benthic-pelagic coupling in the Great Lakes. For example, the physiological condition of abundant benthic invertebrate, *Diporeia hoyi,* which is an important food item for many planktivorous fish, is strongly dependent on the extent of the spring diatom bloom (Gardner et al., 1990; Fitzgerald and Gardner, 1993). Lipid content in this amphipod doubles within a few weeks after the spring diatom bloom and these lipid reserves, primarily triglycerides, serve as the food reserve for months. Not all important links are from the pelagic to benthic region. System productivity is set each winter/spring period by the regeneration of nutrients from the sediments. This important process is critical for establishing the size and extent of the spring bloom and many other processes throughout thermal stratification (Brooks and Edgington, 1994; Scavia et al., 1986).

Recent changes in the Great Lakes, including but not limited to eutrophication, accumulation of xenobiotics, and colonization of nonindigenous species have altered several important links between the pelagic and benthic regions. The most well documented example of this is the recent establishment and proliferation of zebra mussels (Nalepa and Schloesser, 1992), (see section below). In Lake Erie, zebra mussel colonization had a significant affect on phytoplankton abundance, light penetration, and even system productivity (Nichols and Hopkins, 1993; Leach, 1993).

Mussels

The adult zebra mussel was first found in North America in June 1988 (Hebert et al., 1989). This species probably was first introduced into the Laurentian Great Lakes as veligers in Lake St. Clair in 1986 (Griffiths et al., 1989). Between 1988 and 1989, the mussels began to exert significant ecological and economic effects on the eutrophic environments of Lake St. Clair and western Lake Erie. During this time period, the Secchi disc transparency increased in western Lake Erie by 85% and chlorophyll a values declined by 43% (Leach, 1993). While some of these changes certainly may have been the result of some other ecological or environmental factors, there was a dramatic increase in the abundance of adult mussels in the lake during this same time period. In fact, abundances approached 350,000 m^{-2} in some areas of Lake St. Clair (Griffiths, 1993). Zebra mussels represent a significant manipulation to the native ecosystem. They have nearly eradicated native unionids from the regions where they are most abundant.

Furthermore, these bivalves can filter as much as 500 ml $animal^{-1}$ h^{-1} and in western Lake Erie, it is estimated that they filter 40-100% of the entire water column per day (Bunt et al., 1993). A significant amount of work has examined the impact of zebra mussels on planktonic and benthic production in the lower Great Lakes. Fahnenstiel et al. (1995), found that after the establishment of zebra mussels in Saginaw Bay, Lake Huron, benthic primary production increased whereas pelagic primary production decreased. It appeared that Saginaw Bay went from a system dominated by phytoplankton to one where benthic (microalgae and macrophytes) and pelagic producers contributed equally to total primary production.

Overall, recent research has facilitated a better understanding of this "perturbation" and putting us in a better position to take it into account with respect to alterations in benthic-pelagic coupling. Since the invasion of mussels into western Lake Erie in 1987, mussels have markedly impacted pelagic phytoplankton. At the same time, the benthic invertebrate diversity and production have also been affected by mussels (Griffiths, 1993), probably because of organic matter deposition as a result of mussel feces and pseudofeces production. It has been argued that the mussels have changed the lower Great Lakes from a system dominated by pelagic production to one dominated by benthic production and biomass (Mackie, 1991).

In addition to the shifts in invertebrate species composition and biomass in the benthos, there are likely to be some major biological, geological and chemical changes occurring in the Great Lakes as a result of the zebra mussel invasion. Specific biological, geological and chemical changes likely to occur in regions where zebra mussels are abundant include: 1) increased organic carbon deposition into shallow water sediments; 2) increased resuspension and degradation of organic carbon in shallow waters; 3) increased sediment oxygen demand and possibly denitrification rates; and, 4) increased nutrient regeneration rates and possibly changes in the relative availability of N and P. Heterotrophic bacterial growth rates and oxygen consumption increase in response to increases in organic matter availability (Hopkinson and Wetzel, 1982; Wetzel, 1983), and the mussels have high rates of oxygen consumption themselves (Quigley et al., 1993; Cotner et al., 1995). Recent evidence suggests that sediment deposition and resuspension have increased in Saginaw Bay since zebra mussels became established. Increased deposition and anaerobic microzones could contribute to greater substrate availability for denitrifying bacteria in the sediments. Measurements in Saginaw Bay indicate that mussels are increasing denitrification rates and ammonium regeneration rates in this system (Cotner et al., 1995). Increased losses of N through denitrification would decrease the ratio of N to P available to phytoplankton and potentially select for N_2 fixing cyanobacteria. Effects on microbial benthic processes may be further disturbed by the newly invasive quagga mussel because this species can settle on soft sediments.

Macrophytes

There have been recent increases in aquatic macrophyte abundances in shallow regions of the Great Lakes. These increases may be related to a number of factors, one of which may be increased water clarity as a result of the proliferation of the zebra mussel in eutrophic regions of the lower lakes. Increased macrophyte abundance may be further facilitated by decreased nutrient input and increased water clarity associated with the rigorous eutrophication-abatement practices implemented in the watershed since the 1970's. Increased water clarity may shift primary productivity from the pelagic (phytoplankton) to littoral (macrophytes) and/or benthic regions of meso- to eutrophic segments of the Great Lakes.

Impact of the pelagic system on the benthic system

Seasonality plays an important role in mediating potential trophic and biological, geological and chemical impacts of the pelagic on benthic zones. During stratification, the hypolimnion and benthic system are largely sinks for particles settling out of the epilimnion. This interaction is strongly depth-dependent and more frequent in shallow waters. There is ample evidence that all phytoplankton do not have an equivalent impact on benthic production in terms of the nutrition that they provide. A significant proportion of the lipid required by benthic macroinvertebrates is provided by the spring diatom increase (SDI) in Lake Michigan and this lipid enables them to survive the summer period when fluxes of carbon to the sediments are less (Gardner et al., 1990). How important are physical factors (onset of stratification, temperature, and cross-shelf transport) in the development of the SDI? Do changes in the physical characteristics have a significant impact on the benthos through the SDI?

A potentially-significant habitat which may yield relevant information is the hard bottom "cobble reefs" that occur in the nearshore of Lakes Michigan and Huron (and possibly other locations). To our best knowledge, little work pertaining to the questions posed above is being conducted on these reefs (except for zebra mussel research in Saginaw Bay), despite their attractiveness as potential model interactive systems. How productive are these systems? Specifically, what is the relative importance of benthic vs. planktonic microalgal production? What is the role of the benthic invertebrate community and how is it likely to differ from that in muddy or sandy sediment habitats? What are their additional trophic roles in early life histories of fish and fish spawning habitats?

Benthic impacts on the water column

The sediments are an important source of materials that replenish nutrients as well as contaminants into the water column in southern Lake Michigan. See Figure 1 (Eadie et al., 1984). External loading of P was only 18% of the amount resuspended from the sediments at a 100 m station. It was estimated that resuspension of PCBs was double external loading of this contaminant to the water column (Eadie et al., 1984). This model was constructed for a 100 m deep site. It was found that winter fluxes of P from the sediments were three times as great as summer fluxes (Eadie et al., 1984). However, in shallower regions, the benthic-pelagic connection may be tighter, even in summer, because of shorter diffusive distances and greater contact of epilimnetic water with these sediments. How important are nearshore nutrient fluxes in maintaining nearshore productivity in summer? Similarly, is there evidence that regenerated nutrients and resuspended particulate matter from the nearshore region may be important in stimulating offshore production through cross-shelf transport processes?

In many respects, sediment-nutrient exchange is still an open question in the Great Lakes. There is a myriad of models for predicting nutrient (specifically P and N) release from freshwater sediments, but none work well enough to qualify them as generally useful. Specifically, models have not successfully and meaningfully predicted direction and magnitudes of exchange. Very little sediment digenesis work has been completed (Klump et al., 1989). Based on known circulation features and perturbations, episodic resuspension may be of additional importance in the mediation of sediment-water nutrient exchange.

Phosphorus diffusing through pore waters even from relatively shallow depths (<1 cm) must often pass through a sharp oxic/anoxic boundary within millimeters of the sediment-water interface, even in organic rich sediments. Given the well known adsorption of phosphorus on oxidized sediments, this process may effectively "cap" phosphorus release and reduce the actual flux under disturbed conditions where diffusion is the controlling mechanism of sediment-water chemical exchange. Phosphorus releases during resuspension events cannot be quantified in this manner, and therefore remain an unknown.

Measurements of phosphorus exchange between sediments and their overlying waters collected elsewhere in freshwater environments do little to help clarify phosphorus recycling and retention rates in deep Great Lakes sediments. Among studies conducted in lakes, phosphorus exchange under aerobic conditions can only be described as highly variable, and sometimes even negative (Holdren and Armstrong, 1980; Twinch and Peters, 1984; Nurnberg, 1984; Conley et al., 1988; Larsen, 1994). In Lake Michigan, this process has been hypothesized to be controlled by phosphorus demand within the overlying water which lowers phosphorus concentrations below the geochemical equilibrium for the solubility of sedimentary phosphorus phases (Brooks and Edgington, 1994). Under this hypothesis, phosphorus release to the overlying water is biologically-driven from above and is not solely described by digenetic processes within the sediments. One can conclude that models of phosphorus release from sediments based upon correlations with sedimentary conditions, concentrations, lake type, phosphorus loading, etc., are difficult to apply in a universal way.

In addition, biological, geological and chemical interactions within the sediments can alter the water-column nutrient signature. Sediments do not behave as a passive bioreactor, but rather, alter the relative abundance of C, N and P available in the water column. The release of N and P from sediments is an important source of recycled nutrients for algal production in overlying water (Boynton and Kemp, 1985). The regeneration of both N and P to the overlying water is complicated by chemical and biotic factors. Nitrogen regeneration in sediments is affected strongly by oxygen availability but unlike phosphorus, microbial denitrification can release significant amounts of gaseous nitrogen to the atmosphere. Many of the factors that stimulate N-regeneration in the sediments also stimulate nitrification and denitrification rates. Processes that release nitrogen from lakes as gases result in a net export of nitrogen from the system and may affect the productivity of the lake. Sediment effects on N and P regeneration can have significant impacts on phytoplankton species composition by changes in the availability of these nutrients as well as silica and possibly some micronutrients (Sterner, 1989 and 1990).

2.0 Important/Guiding Questions

In order to better understand the lake ecosystem, the role of the material exchange between benthic and pelagic systems should be clarified. We need to better understand how this coupling is involved in the cross-shelf transport of material from the lake shore to deep depositional areas, and how these processes are affected by wind events, which effectively drive the circulation in all of the lakes.

Sub-questions:

- What is the relative importance of "acute" external large storms versus "chronic" internal processes (such as upwellings and downwelling) that occur during more quiescent conditions?
- How does the setup and destruction of the thermocline affect benthic-pelagic exchange?
- What are the rates of transfer of material across the shelf, and how variable is this rate?
- How do these processes affect the distribution of material to the deep lake floor?
- How do resuspension and deposition interact with the biology and geochemistry of the sediment-water interface to affect benthic-pelagic coupling?
- What are the processes responsible for the existence and maintenance of benthic nepheloid layers, and what are the mechanisms through which benthic nepheloid layers affect benthic-pelagic coupling?

It is additionally important that we advance our knowledge and understanding of unique but important circulatory features such as vortex structures and their functional relationships to furrow and other bottom topographic features. Are vortex structures present even in the absence of furrows? If so, do they then meander so that sediment properties are homogeneous on the scale of tens of meters? What specific conditions are required for the formation of these and other bottom features, and how widespread are these bedforms in the Great Lakes?

3.0 Approach

In order to achieve the above goals, a combination of long-term time-series measurements of currents, waves, water temperature, water transparency, and chlorophyll needs to be combined with more intensive physical, biological, and biological, geological and chemical sampling before and after various "events". Innovative approaches to intensive sampling during events are also needed. Measurements should be made at several sites on a cross-shelf transect in order to document differences with depth. Sediment traps and bottom collections also need to be made to document the vertical sediment flux and bottom properties.

In this regard, profiling current meters (e.g., the Cyclesonde) and specially designed acoustic Doppler instruments are well suited to investigations of the large-eddy structure in the BBL. Side-scan sonar and sediment sampling, including sampling with a submersible ROV, are the principal field techniques needed for associated sedimentological investigations.

From geological, chemical and biological perspectives, process-related information relevant to an improved understanding of benthic-pelagic coupling include:

1. primary productivity (chlorophyll, P vs. I curves)
2. phytoplankton community structure
3. moored measurements (at a near- and offshore site to look at cross-shelf transport among other processes): fluorometers, sediment traps, current meters
4. sediment oxygen demand/ nutrient fluxes measured with *in situ* chambers
5. sediment nutrient concentrations: inorganic N, DON, PON, inorganic P, DOP, POP, DIC, DOC, POC, etc.
6. some measurements of lateral transport of nutrients, either dissolved or particulate
7. lipids as indicators of energy flux from pelagic to benthic environments
8. bacterial production and biomass
9. measurements of pelagic nutrient cycling (N and P), i.e., fluxes
10. measurements of macrobenthic biomass and production

11. measurements of microbial growth rates in sediments

12. fish recruitment, biomass and production

Integrated physical and biological, geological and chemical studies also are needed to understand mechanistic connections between forcings and responses. For example, real advances in understanding the role(s) of benthic nepheloid layers will require coordinated investigations of the physical factors that control their development and maintenance and the biological, geological and chemical factors that determine their importance for benthic-pelagic exchange. In this regard, basic theoretical studies and more applied modeling investigations are an important complement to field work.

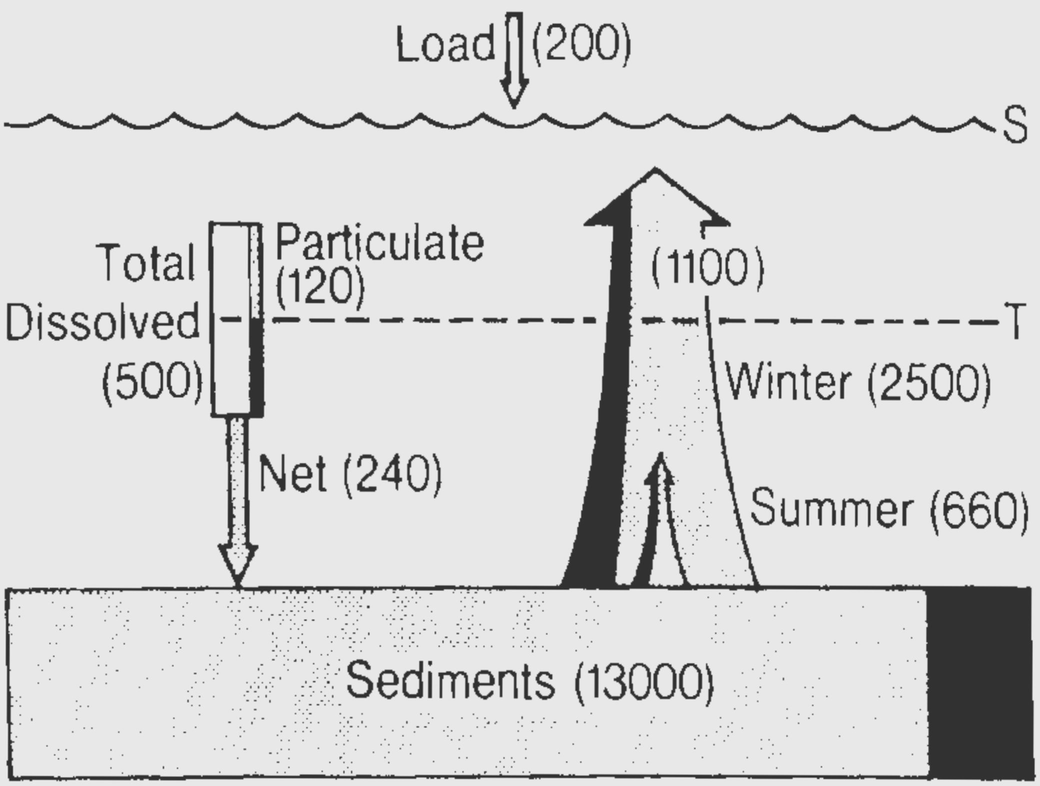


FIGURE 1. Phosphorus budget for a 100 m deep, 1 m^2 water column in southern Lake Michigan. Shaded areas represent particle-bound phosphorus. Black areas represent 0.1 N NaOH extractable P. Numbers in boxes (reservoirs) have units of mg P. Numbers associated with arrows (fluxes) have units of mg P/m^2/yr. Widths of arrows and boxes are proportional. T (dashed line) represents the thermocline. (Figure 12, Eadie et al., 1984)

F. Air-Sea Interactions

Chairperson: Dave Armstrong

Rapporteur: Eugene Terray

1.0 Background

Air-sea interactions play a key role in controlling fluxes of materials, energy, heat and momentum in coastal areas (Brink et al., 1992). These fluxes have a major influence on the physics, chemistry and biology of the Great Lakes. The importance of air-water fluxes in controlling the chemistry of the Great Lakes is well-recognized (Eisenreich and Hornbuckle, 1995). Loadings of organic chemicals, metals and nutrients to the Great Lakes are strongly influenced by transfer of materials between the atmosphere and the lakes. Air-water fluxes are a major component of the mass balance for organic chemicals such polychlorobiphenyls and polycyclic aromatic hydrocarbons in the Great Lakes. Thus, understanding rate of recovery of the Great Lakes as sources of these chemicals are reduced or eliminated requires accurate information on air-water fluxes. Over the past several decades, the atmosphere has been a major source of PCBs. However, recent evidence suggests that the lake to atmosphere flux is an important component of the mass balance (Manchester-Neesvig and Andren, 1989; Achman et al., 1993). Similarly, the Great Lakes may be a source for transfer of terrestrial carbon to the atmosphere as carbon dioxide (Cole et al., 1994). Thus, it is uncertain whether the Great Lakes are a net sink or source of several chemical substances, including PCBs and carbon dioxide.

The Great Lakes provide excellent sites for furthering our understanding of air-sea fluxes. First, the Great Lakes can be treated as "closed systems" where closing the mass balance is feasible. Furtbermore, access to appropriate sites for making the needed experimental measurements is good. Thus, the Great Lakes are particularly well-suited for developing an understanding of air-sea interactions which can be transferred to other coastal areas.

Fluxes of materials, energy and momentum at the air-water interface have a major influence on the biology of the Great Lakes. Thermal gradients, currents and mixing structure habitats for plankton and higher organisms, resulting in spatial and temporal gradients in populations and foodweb structure. Thus, understanding and modeling biotic species and communities requires a coupling of air-lake interactions to their influences on aquatic organisms and biological, geological and chemical processes.

Several important areas concerning the chemistry, physics and biology of the Great Lakes can be identified where research is needed to advance our understanding of air-water interactions and their influence on the Great Lakes and other coastal areas. However, we believe that one of the main problems is an inadequate understanding of the physics of air-water interactions. In particular, improved information is needed on mass transfer coefficients governing the transfer of gases at the air-water interface. At present, mass transfer coefficients representing "average" conditions are often used, leading to major uncertainties in constructing chemical mass balances involving air-water fluxes. The uncertainty in mass transfer coefficients arises largely from limited data and few opportunities for measurements made under actual field conditions with appropriate correlative variables. A major need exists for making accurate measurements of gas fluxes and associated mass transfer coefficients as related to key variables in the system, including wind speed, wind duration and direction, turbidity, surface currents, surface slicks and thermal convection. After quantification of fluxes as a function of local conditions, research is needed on models to scale up to the regional or whole lake scale using remotely sensed data reflecting key variables controlling mass transfer coefficients. Transfer of particles as well as gases is often a major component of chemical fluxes. Thus, concurrent measurements of particle fluxes should be make to provide data for advancing the modeling of particle fluxes.

2.0 Important /Guiding Questions

Our two main questions are as follows:

1. What are the surface fluxes of heat, momentum and materials in the coastal region?
2. What are the mass transfer coefficients governing the transfer of gases across the air-water interface, and how do mass transfer coefficients vary with time and space as controlled by key physical, chemical and biological variables in the system?

Sub-Questions:

- What are the quantitative influences of wind speed, cold fronts (convection), surface waves, surface microlayers and reflectance on surface fluxes and mass transfer coefficients?
- What are the fluxes of particles at the air-water interface, and what is the relation of particle size and concentration to fluxes?
- How can scale-up from fine-scale, high resolution measurements be accomplished?
- How do surface fluxes of heat and momentum drive upper layer mixing?

3.0 Approach

A series of field experiments would be conducted with the emphasis on accurate, concurrent measurements of surface fluxes and associated physical parameters. The results would then be used to refine and parameterize models of fluxes at the air-water interface.

3.1 Site Selection Criteria

The measurements and experiments would be conducted at various times and locations to provide information on important variables controlling physical conditions at the air-water interface. Investigator teams would propose sites and platforms best suited for obtaining data on the variables to be investigated.

3.2 Planned Observations/Data

Physical measurements would be coupled with measurements of gas and particle fluxes. The gases would be chosen to represent different physical-chemical properties and should be compatible with accurate, fine scale measurements. Eddy correlation and accumulation approaches would be used to give accurate flux measurements. Concurrent with flux measurements, key physical variables would be measured including wind speed, wind direction and duration, surface currents and waves, humidity, surface tension, temperature structure above and below the interface, turbidity, water depth, upwelling and ice break-up, both long and short wave radiation, and intensity of turbulence below the air-water interface. The correlative variables are essential for model development.

The influences of heat and momentum transfer on the structure of the mixed layer would also be assessed. Investigators would propose associated investigations of influences of aquatic biota and biological, geological and chemical processes.

Fine scale flux and physical parameter measurements would be coupled with measurements over a larger scale, possibly using remotely sensed data, to facilitate scale-up of transfer coefficients for application to whole lake flux estimates.

Top priority would be given to flux measurements of substances which represent different physical chemical properties and which can also be measured accurately on short time scales. Mass transfer coefficients could then be transferred to other substances of similar properties. Candidates are oxygen, water vapor and carbon dioxide. Other substances would be measured to provide information on particle-associated fluxes (e.g., particle mass, sulfate). We also have strong interest in other substances of high importance in coastal regions (nitrogen, phosphorus, nitrous oxide, methane, DMS, metals, chemical contaminants) and recommend concurrent flux measurements of theses substances where feasible.

3.3 Modeling Needs

The basic framework for modeling the fluxes of materials, momentum and energy at the air-sea interface is well-developed (Atlas and Giam, 1986; Jahne, 1991; Schwarzenbach et al., 1993; MacIntyre et al., 1995). The main needs are accurate data for parameterizing these models so that quantitative flux estimates can be obtained as related to spatial and temporal physical factors governing mass transfer. Thus, we believe the main focus of modeling will involve use of existing models which would be refined and parameterized. Models likely to be used include the surface renewal model. This model, discussed by MacIntyre et al. (1995), has the potential for high predictability in a variety of situations, as it includes the effects of winds, thermal convection and waves on the turbulence below the air-water interface which strongly governs the rate of gas exchange. With the new, easily deployed instrumentation now available for turbulence studies, the coefficients for the surface renewal model can be accurately assessed.

3.4 & 3.5 Instrumentation Needs and Sampling Platforms

Instrumentation needs include meteorological stations and turbulence-microstructure profilers. The latter instruments are needed to quantify energy dissipation rates at the air-water interface.

We envision the use of mainly three types of platforms, depending on the type of experiment and measurements needed. The combination of complementary measurements using these platforms would provide a comprehensive data set for key parameters.

- In-lake sampling towers such as the CCIW Tower in Lake Ontario provide a good platform for mounting instruments for precise measurements. Measurements can be made over short or long time scales. The main disadvantage is restriction to one location.

- Research vessels provide flexibility for sampling in specific locations chosen for assessment of the influences of site specific variables such as turbidity currents, water depth, currents and surface slicks. Limitations include the duration of data collections and suitability for some instruments.

- Buoys are especially useful for continuous, long-term measurements at remote sites using instruments that can be queried from central locations. However, instruments requiring frequent attention or stable platforms cannot be used on buoys.

The following table summarizes the types of measurements which can be made from the different types of platforms:

Measurement	Tower	Buoy	Vessel
Momentum	✔	✔	✔
Kinetic Energy	✔	✔	✔
Sensible Heat	✔	✔	✔
Latent Heat	✔		✔
Gas/Chemical Fluxes	✔		✔
Dry Deposition	✔		✔
Wet Deposition	✔	✔	✔

4.0 Summary

Fluxes at the air-water interface are a major component of the mass balance of many important substances in the Great Lakes and other coastal regions. At present, these fluxes are highly uncertain due in part to a lack of data needed to parameterize models used to calculate fluxes. We propose a series of experiments involving concurrent measurements of fluxes of key substances and the physical variahles controlling mass transfer. Oxygen, water vapor and carbon dioxide may be good surrogates for modeling fluxes of other gases because detailed flux measurements can be made at high temporal resolution. Eddy correlation and accumulation techniques should be used to give accurate flux measurements. Important physical variables include wind, currents, waves, temperature structure, water vapor pressure, surface tension and turbidity. Several platforms should be used to meet the differing needs of experiments. Complementary data should be collected using in-lake towers, research vessels and buoys. After models are high resolution models are parameterized, the potential for using remotely sensed physical/meteorological data to model mass transfer and material fluxes at regional or whole lake scales should be developed.

G. Land-Margin Effects

Chairperson: Brian Eadie
Rapporteur: Craig Sandgren

1.0 Background

The Laurentian Great Lakes are a major resource to all of North America, containing 20% of the worlds' surface fresh water and 90% of the surface fresh water of the United States (Tilzer and Bossard, 1992). They serve as the focus for multi-billion dollar tourist and recreation industry (Fed. Res. Bank of Chicago, 1991), supply 40 million people with drinking water, provide habitat for wildlife and 250 species and subspecies of fish (with an annual commercial and recreational value of approximately $4 billion: USFWS, 1990), and support transportation and diverse agricultural production. The basin serves as home to 15% of the U.S. and 60% of the Canadian population.

The problems in the Great Lakes coastal region (excess nutrients, anthropogenic contaminants, competitive resource use) are common to many densely populated systems, but they are compounded by the environmental pressures of a large fraction of U.S. and Canadian heavy industry and long (decade to centuries) water renewal times. One of the big advantages of the Great Lakes over marine coastal systems is that, while they are still large systems and are mediated by similar processes, they are more tractable: easier logistics, more bounded physically, simpler ecological structure and functioning. The lakes have benefited from ecosystem management policies implemented over the past two decades.

The lakes are sensitive systems because of low biotic diversity as compared to marine ecosystems and because of their long hydraulic residence times. The Great Lakes have suffered a century-long history of perturbations involving both biological (fish stocking, dramatic invasions by nonindigenous fish and invertebrate species) and chemical (excess nutrient, organic and metal contaminants) agents. They are now a highly managed system with eight states, one provincial government, several federal agencies and international treaties all playing a role.

The land margin of the Laurentian Great Lakes constitutes roughly 20% of the total coastal margin of the contiguous United States. The Great Lakes shoreline is composed of a mosaic of bays, channelized rivers and streams, urbanized harbors, coastal wetlands, and long stretches of beaches and cliffs. Coastal geomorphology includes exposures of crystalline rock, several types of glacial clays, tills and outwash plains (sands, gravels), and late-glacial aeolian dune fields. Erosional problems along Great Lakes coasts characterized by fine-grained materials have been well-documented particularly in association with long-term (decades, centuries) trends in changing lake water levels

(NOAA, 1986) the financial and social costs of such coastal erosion are large. Transport and remobilization of sedimented nutrients and toxicants by nearshore erosion may also be a serious concern. Coastal scouring by winter ice has been a particularly difficult erosional process to study (Folger et al., 1994). It seems clear that the potential importance of ice scouring in the Great Lakes may be as important as has been documented for marine estuaries, where it plays a major role in bulk transport of organic material out of coastal regions at some times of year.

Food web dynamics and biologically-mediated processes within the land-margin zone play critical roles in determining the fate of organic matter in the Great Lakes. The nearshore environments (less than ca. 10m water depth) are the nursery grounds for most forage and piscivorous fish species, with individual species requiring different mixes of water quality and substrate conditions for successful recruitment. Such fish carry the "signature" of their coastal experience as identifiable stable isotope signatures when they subsequently migrate offshore. The land-margin is also the primary biological buffer and sponge for watershed inputs to the lakes. Allocthonous inputs of living organisms, organic materials, nutrients and contaminants coming from watershed and riverine sources are integrated into the Great Lakes' food webs and their biological, geological and chemical transport and transformation processes largely within the land-margin zone. As a result of such allocthonous inputs, as well as repeated assaults from coastal hydrodynamic mixing events, the biological communities of coastal regions within the Great Lakes are distinctly different from offshore communities. They also seem to be very robust, having strong capacity to reorganize after perturbations (see Transformations working group report, Appendix 2.H.)

The Great Lakes region is at the forefront of the careful, balanced management of a fragile resource. The program described herein is intended to provide better quantitative understanding of the role of the land-margin boundary in mediating the dominant transport and transformation processes affecting organic material and living organisms in the Laurentian Great Lakes.

2.0 Important/Guiding Questions

Land-Margin Effects relevant to CoOP Issue

Two questions are posed, one dealing with materials flux into the land-margin from the surrounding watershed and the second dealing with material flux within the land-margin zone itself.

1. What are the relationships between the sources and fates of Allocthonous inputs to the coastal land-margin zone?

The fate of dissolved and particulate allocthonous inputs must be one of the following: remain in solution or suspension, undergo chemical transformations including possible entry into the biological food web, burial, or transport without modification out of the land-margin zone. Because of the mosaic nature of Great Lakes coastlines, allocthonous materials entering the coastal zone may be derived from a number of sources, specifically: rivers with estuaries, channelized rivers and streams, coastal wetlands, nonpoint (run off) sources, and groundwater. Inputs from such sources will vary with regard to critical characteristics such as: (a) the relative magnitude and temporal dynamics of the input from each source; (b) the relative importance of dissolved versus particulate materials in the flux; (c) the chemical composition and size of input particles, which play an important role in subsequent particle transport and transformation within the land-margin; and (d) the relationship of inputs to land use characteristics along the coast and within the watershed.

To answer this general question, there is, first of all, a need for an adequate comparative database of allocthonous inputs characteristics (i.e., dissolved vs particulate, particle size, chemical composition) for the various sources listed here. Such data must be collected with regard to the time dependent input flux to quantify adequately the natural variance spectrum. Then, experimental studies are required to link the flux (time X magnitude) and "quality" (availability to transformations) of inputs to their resolved fates.

2. What are the consequences with regard to materials flux and transformation of the major erosional and depositional processes within the land-margin zone: winter ice scouring, wave-driven coastal erosion, sediment resuspension related to longshore water movements, fluvial plumes?

Each of these processes has the capacity to transport particles, to disrupt by burial or scouring established biological and geochemical processes on-going at the sediment surface, and to (except for fluvial plumes) mobilize previously buried toxicants, organics and nutrients. Ice is most effective with regard to sediment disturbance in conjunction with fine-grained sediments and in those lakes in which open water persists during the winter, permitting cycles of freeze-thaw and wave-driven ice movements. Ice-mediated transport of biologically, geologically and chemically important materials is virtually unknown for the Great Lakes, as is the impact of ice on shallow water biological communities. The influence of ice on nearshore water circulation patterns and the transport of fluvial or watershed inputs to the Great Lakes are also poorly known. Wind and wave-driven coastal erosion is a major source of particulates to the coastal water column, but the impact of coastal erosion on established *in situ* processes within the Great Lakes land margin zone is unknown. There is certainly decreased light penetration to drive photosynthesis and increased probability of disrupting biological activities on the sediment surface, but there is also the potential for nutrient enrichment. Sediment resuspension driven by longshore currents represents a case of internal sediment-water column recycling within the coastal land-margin zone. Such events are highly stochastic in both time (initiation, duration) and space (areal extent, specific locales), but given baseline data regarding quantitative estimates of resuspended nutrients and organics, lateral transport can be modeled from current and developing models of basinwide circulation patterns. Both longshore currents and fluvial plumes constitute a mechanism for long distance transport of living organisms and their propagules (spores, pelagic larvae, seeds). They thus serve to repeatedly inoculate habitats, insuring the potential for homogeneity within nearshore biological communities as well as the rapid spread of nonindigenous species. While longshore currents transport organisms longitudinally within the coastal land margin zone, fluvial plumes may push nearshore organisms laterally into offshore habitats and also serve to inject riverine organisms into the coastal zone. Along with organisms, fluvial plumes inject nutrients and both inorganic and nonliving organic particles. Such events could modify existing processes within the land margin zone by: nutrient stimulation, increased burial rates, reduced light intensity, and chemical and particulate flocculation of preexisting nutrients and organisms. The response to river plumes within the land margin zone will likely be different for channelized versus estuarine river systems and also depend on both watershed and input flux characteristics.

3.0 Approach

Existing information on important nearshore processes affecting the coastal environment will be assimilated, including shoreline erosion, nutrient and contaminant sources, contaminated sediment resuspension and transport, and ecological response. From an analysis of these data, a detailed program for information collection and process studies will be designed.

3.1 Site Selection Criteria

We recommend the use of comparative, generic coastal types in order to examine fully the range of responses inherent in research questions. Depending on adjacent land use, there could be several subcategories for each type. These types are:

- Straight coasts with bluffs and beaches, but no significant tributaries
- Estuaries and bays
- River channels
- Coastal wetlands

3.2 Planned Observations/Data

- Time series of selected constituent fluxes from bluffs, tributaries, and groundwater
- Quantification of sediment and associated constituent resuspension
- Biological response to high energy events (e.g., scouring, recolonization)

- Biological processing of inputs from diverse sources (bioavailability, productivity)
- Quantification of seasonal wave, current and ice dynamics at the land margin

3.3 Modeling Needs

- High resolution (nested grid, <1 km) transport and wave models
- Hydrologic (river input) models
- Appropriate ecological process models
- Models of coastal erosion
- Sediment resuspension and transport
- Ice dynamics in the nearshore

3.4 Instrumentation Needs

- High resolution (aircraft) remote sensing
- Integrated nearshore instrument package (currents, waves, particles, biology, productivity)

3.5 Sampling Platforms

- Small, high speed vessel(s)
- Manned tower/platform for time series measurements unattainable from remote instruments
- Shore-based lab with pumped water for continuous measurements of measurements unattainable from remote instruments

3.6 Products

The issue of final study products is important because a diversity of outputs will be required, depending on the target audience. Technical reports, data bases and documented computer programs are necessary for completeness and as primary source materials. Publication of findings in peer-reviewed journals is necessary to establish scientific credibility. It is crucial to communicate study program results to senior managers and sponsors in the form of management-level synthesis documents and executive summaries. Other useful study products are workshops and PC-based demonstrations that emphasize use of study results to address critical management questions.

Specific products will include:

- Publications/reports in scientific literature that describe the nature and magnitude of "key" processes

- Climatological data base for coastal regions of the Great Lakes
- User-oriented models
- Enhanced network within the Great Lakes resource management community
- Products for the general public available through parks, schools, etc.

4.0 Summary

This report deals with the coastal land-margin zone of the Great Lakes, extending to about 10 meters water depth. This zone acts as both a buffer and sponge for allocthonous inputs to the lakes, and it is characterized by a number of highly dynamic physical processes that influence the transport and transformations of biologically, geologically and chemically important matter. Critical issues that need analysis include the linkages of both the allocthonous and *in situ* sources of biologically relevant materials with the physical, chemical and biological transport and transformation processes active within the coastal land-margin. The diverse potential sources of materials to the land-margin zone and the mosaic nature of the coast line lobby for a comparative study approach incorporating a program of input and transport monitoring from the diverse input sources plus experimental exercises to measure transformation rates and modelling efforts to couple hydrodynamics with geochemical mass fluxes and biological responses. The comparative approach must be robust with regards to evaluating both the spatial and temporal variability in forcing functions. Of particular concern are: (1) characterization of allocthonous inputs with regard to dissolved versus particle nature and particle chemical composition; (2) biological response within the land-margin zone to allocthonous inputs from diverse sources; (3) how physical processes within the land-margin zone determine the resuspension and deposition of particulate matter and associated constituents; (4) how the formation, movement, and thawing of the ice influences the processes of lake physics and the accumulation, storage, and transport of sediment, nutrients and living organisms; and, (5) the effects of episodic loading and resuspension events on biological community structure, trophic dynamics and habitats.

H. Transformation of Solutes, Particles and Organisms

Chairperson: John Lehman

Rapporteur: Wayne Gardner

1.0 Background

Lake mixing and productivity relations

Existing evidence indicates that for all the Great Lakes except Erie, which typically freezes during winter, the isothermal mixing period (winter and spring) is a time of energetic redistribution of materials which recharges the water column with nutrients (Fig. 1: Eadie et al., 1984). Most of the annual primary production occurs at the end of this period, when daylength increases sufficiently for positive net photosynthesis in the water column possible. This spring diatom bloom ends when nutrients become exhausted or when thermal stratification develops (Brooks and Edgington, 1994). It is during the spring bloom that large, long-lived copepods and macrobenthos gain lipid nutritional stores (Fig. 2: Gardner et al., 1989), which help sustain them through the summer months of low primary productivity (Fig. 3: Gardner et al., 1990; Cedarwall, 1977; Fitzgerald and Gardner, 1993; Quigley, 1988), and provide energy resources needed for reproduction (Vanderploeg et al., 1992).

Plankton communities established in inshore and offshore regions after the spring diatom bloom are fundamentally different. Changes occur in the size structure of the primary producer community as large diatoms become scarce (Fig. 4). In the inshore, phytoplankton biomass drops and dominance shifts to species with lower sinking rates than diatoms. In the zooplankton community dominance shifts from copepods, which produce compact fecal pellets, to Cladocera (Fig. 5: Scavia and Fahnenstiel, 1987), which produce uncompacted feces. The relative importance of *in situ* recycling, external inputs (rivers, rain, dryfall), vertical eddy diffusion, and lateral advective transport and mixing in maintaining this biological community are unknown. In the offshore, epilimnion phytoplankton biomass drops below inshore values, deep chlorophyll maxima appear, and large-bodied zooplankton dominate. It is virtually certain that the offshore phytoplankton community is principally dependent on nutrients recycled *in situ*, which were originally made available during the previous isothermal mixing episode (Brooks and Edgington, 1994; Fee et al., 1994). However, it is unknown how much offshore production processes depend on episodic perturbations to the nutrient balance resulting from physically driven processes such as upwelling and excursive gyres from longshore currents.

Inshore-Offshore Gradients and Cross-Shelf Community Structure

Comparison studies between communities of alternative organization are the logical next step in Great Lakes plankton investigations. The existence of distinct inshore and offshore communities derived from a common species pool and maintained despite cross-shelf mixing argues for the existence of strong organizing forces.

The Great Lakes have two important predation gradients: fish planktivory, which decreases from inshore to offshore, and invertebrate planktivory which varies inversely to fish planktivory. Spatial distributions of nearshore fish are constrained by the thermal preferences of the fish and the physical intersection of the thermocline with the sediments (Brandt et al., 1980). Evans and Jude (1986), note that intense fish planktivory in inshore areas is a consistent feature of Lake Michigan. More recent work (Lehman, 1991; Lehman and Caceres, 1993), identified the opposing gradient in invertebrate planktivory. The net result is an inshore zooplankton community dominated by small species (*Bosmina longirostris, Daphnia retrocurva*) that are less susceptible to predation by fish predators. Some of the large-bodied offshore zooplankton species prey effectively on these small species. Thus, the intensity of fish planktivory may be the underlying reason for the inshore/offshore differences. Figure 6 shows typical inshore and offshore summer plankton communities in Lake Michigan; some changes in population abundances are associated with a thermal front, but not all taxa are affected. Despite the frequency of upwelling, inshore communities reestablish themselves after each physical displacement and maintain a consistent structure through time (Figure 7).

Predation alone may not be the cause for the cross-shelf compositional differences in zooplankton communities. Phytoplankton differ between the regions, and differences in food availability or food quality may be important. The role that food variation plays in zooplankton community structure is unknown and should be investigated by direct experimentation. There are differences in bacterioplankton abundance (Moll and Brahce, 1986), and presumably bacterial productivity as well. These differences contribute to different rates of nutrient regeneration and uptake in the inshore and offshore regions (Cotner and Wetzel, 1991). The offshore and inshore plankton communities probably function at different rates at a variety of trophic levels. Rates of nutrient cycling, trophic transfer efficiencies, and material fluxes are potentially different as well.

Many differences between nearshore and offshore regions may be constrained by the physical environment. For example, nutrient cycling rates are affected by temperature and contact with the sediments (DeAngelis, 1992). Temperature is affected by mixing depth, localized tributary inflow, and circulation patterns, among other factors. Stratification temporally reduces nutrient feedback from sediments in deep regions. This feedback may be important in controlling both productivity as well as phytoplankton species composition through effects on the stoichiometric ratios of nutrient supply. Temporal and spatial separation of phytoplankton and bacterioplankton productivity have been recorded in Lake Michigan (Scavia and Laird, 1987), but any associated effects on composition and operation of food webs are largely unknown.

2.0 Important/Guiding Questions

Does uncoupling in time and space occur for the input processes and their biological effects on the ecosystem components?

Sub-Questions:

- Is lakewide mixing during the isothermal period the major influence on annual scale biological production processes for both inshore and offshore regions?
- Is there little cross-shelf transport of nutrients and productivity during the stratified period such that 90% or more of offshore biological activity is supported by local phenomena (thermal mixing, remineralization, etc.)?
- Are land margin interactions during the stratified period focused on a relatively small volume of the lake with its associated biota?

3.0 Approach

There are distinct inshore and offshore biological communities (algae, zooplankton, and fish) during the stratified season. The study should examine the causes and effects of disturbances to these biological gradients with particular attention to the mechanisms by which they reestablish themselves in the water column.

It will be necessary to develop a practical definition of the inshore zone based on biological as well as physical criteria (including irradiance), and to quantify the fluxes of nutrients and carbon into and out of this region in both isothermal and stratified periods. From strategically placed transects, gradients in dissolved and particulate properties should be measured in directions both parallel and normal to shore; transport of materials released by internal recycling both within the water column and at the sediment-water interface in nearshore regions must be distinguished from those supplied by allocthonous means. It will also be necessary to estimate frequency distributions in both time and space of production rates of phytoplankton, zooplankton, and bacteria. Together, these data will confirm or deny our present understanding about the times and places which dominate biological transformations of materials and energy in the Great Lakes.

3.1 Site Selection Criteria

Sites should have gradients in biological community structure across regions that arc disrupted episodically by upwelling or coastal jet features. In order to evaluate the relative importance of inflows, wet and dry precipitation, lateral exchange, vertical mixing, and *in situ* recycling, it would be desirable to contrast lakes of most different nutrient condition, such as Lake Erie vs. Huron, Superior, or Michigan.

3.2 Planned Observations/Data

<u>Year-Round Measurements</u>

- Provide synoptic measurements of chlorophyll, transparency, and photosynthesis vs. irradiance curves. This activity will permit estimations of *in situ* primary production.
- Deploy moored fluorometers inshore and offshore in order to measure variations in algal abundance.
- As a proxy for algal production and loss, measure changes in bulk inventories of Si, N, P in the water column, and measure particulate C, N, P, and Si in sediment traps.
- Measure sources and turnover rates of P both inshore and offshore. This activity will direct attention to the dynamies of the element most directly limiting to biological productivity in these lakes.
- Measure vertical distributions of dissolved inorganic carbon, alkalinity, and pCO_2 in order to assess bulk biological processes of photosynthesis and respiration at integrative scales.

<u>Stratified Period</u>

- Compare shallow, isothermal regions with deep stratified regions with respect to chemistry, community composition, and biological process rates. The purpose of this activity is to assess the role of exchange processes from sediment to water column in the maintenance of production rates and community structure.
- Measure physical exchange between inshore and offshore regions. This activity will permit estimation of nutrient and material flux rates.
- Distinguish nutrients derived from inshore sources from those derived from offshore sediment. The purpose of this activity is to separate the contribution of lateral supplies of nutrients from those nutrients supplied by vertical mixing.
- Develop pigment indicators of recent production, and measure both pigments and organic C in sediments.

- Measure the vertical distribution and diurnal changes in both primary and secondary biological production, with particular attention to responses to episodic events such as upwelling.
- Partition sinking material among algae, fecal pellets, and detritus.
- Develop and measure biochemical tracers that can identify organic matter of terrestrial origin, and measure stable isotope ratios for C, N, and S in food web components as well.
- Determine how closely consumptive P-demands and N-demands by phytoplankton are met by regeneration *in situ* by zooplankton and microbes. Estimates of seasonal regeneration by benthic invertebrates and microbes should be included in nearshore regions.

3.3 Modeling Needs

A functional circulation model is currently available for Lake Erie, and comparable models are in development for Lakes Michigan and Ontario. These models should provide the necessary initial estimates of physical exchange rates, which can be refined by additional observations. Model development will be needed to combine the physical output with biological process rates.

3.4 & 3.5 Instrument Needs and Sampling Platforms

No instrument development is necessary. However, the program will require moored instrumentation including current meters, sediment traps, *in vivo* fluorometers, and acoustics. Towed instruments should include optical plankton recorders and pump/probe devices for measurement of primary productivity.

Existing vessels are sufficient.

4.0 Summary

Striking differences exist between the plankton communities that occupy inshore and offshore regions of the Great Lakes. Even though a common species pool is shared between these regions, inshore areas are dominated by small-bodied species of zooplankton, whereas much larger bodied species dominate the offshore waters. These plankton communities appear to be maintained by two major planktivory gradients: fish planktivory, which is greatest inshore and which relaxes toward offshore regions, and invertebrate planktivory, which increases from inshore to offshore. However, there are also differences between phytoplankton communities and nutrient availability between these regions, suggesting that the quantity and composition of food resources may also be important. These persistent community differences show that cross-shelf transport processes, which would work to homogenize the communities, are opposed by strong biological structuring forces.

These observations cut to the heart of the CoOP research initiative in that they describe an ecologically important interplay of physical transport rates and biological effects. The data suggest that transport processes, which occur mainly during the isothermal winter and spring periods, are temporally uncoupled from their biological effects, which are manifest as community gradients during summer. This suggests that these ecosystems switch annually between a physically dominated period, when the bulk of the new biological production occurs, and a biologically dominated period, when nutrients are recycled.

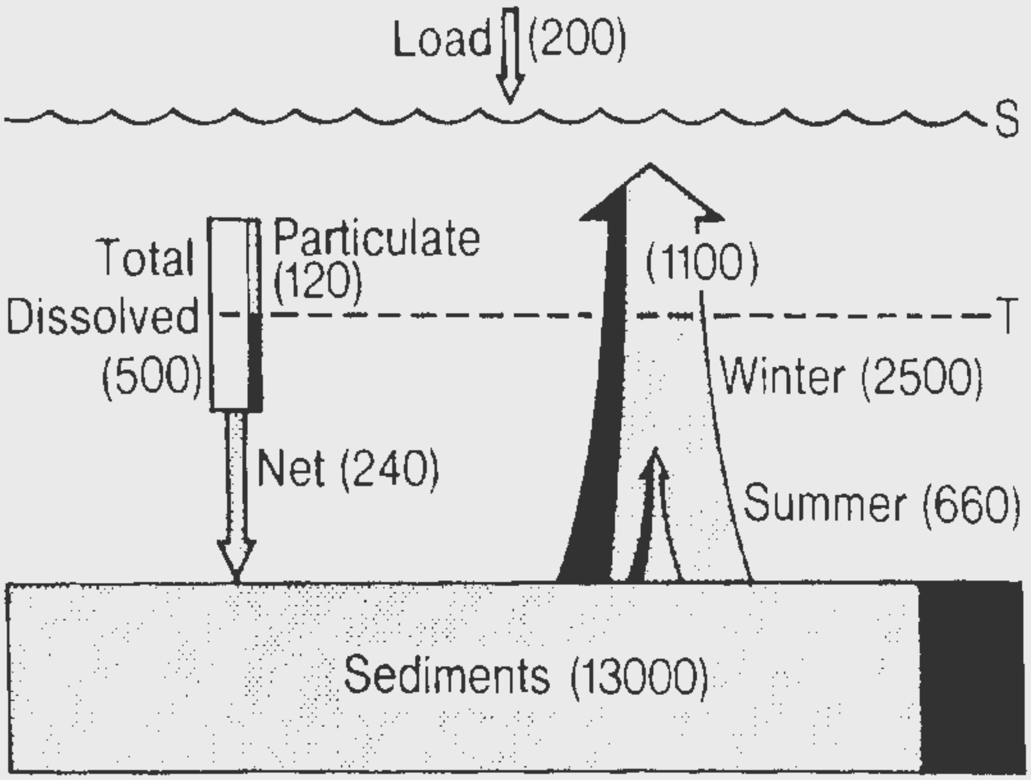


FIGURE 1. Phosphorus budget for a 100 m deep, 1 m^2 water column in southern Lake Michigan. Shaded areas represent particle-bound phosphorus. Black areas represent 0.1 N NaOH extractable P. Numbers in boxes (reservoirs) have units of mg P. Numbers associated with arrows (fluxes) have units of mg $P/m^2/yr$. Widths of arrows and boxes are proportional. T (dashed line) represents the thermocline. (Figure 12, Eadie et al., 1984)

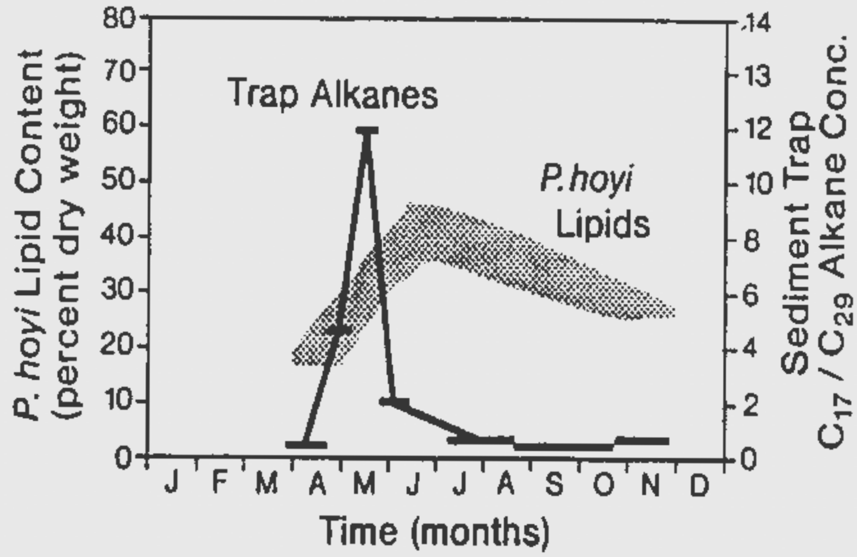


FIGURE 2. Seasonal total lipid content of *P. hoyi* averaged over 2 yr of collection (data taken from Gardner et al. 1985; Landrum 1988; Gauvin 1989). Also shown is the ratio of the planktonic *n*-alkane C_{17} to the terrestrial *n*-alkane C_{29}. The April-June peak is a clear signal of autochthonous carbon input. The sediment value for this ratio is 0.2. (Figure 7, Gardner et al., 1989)

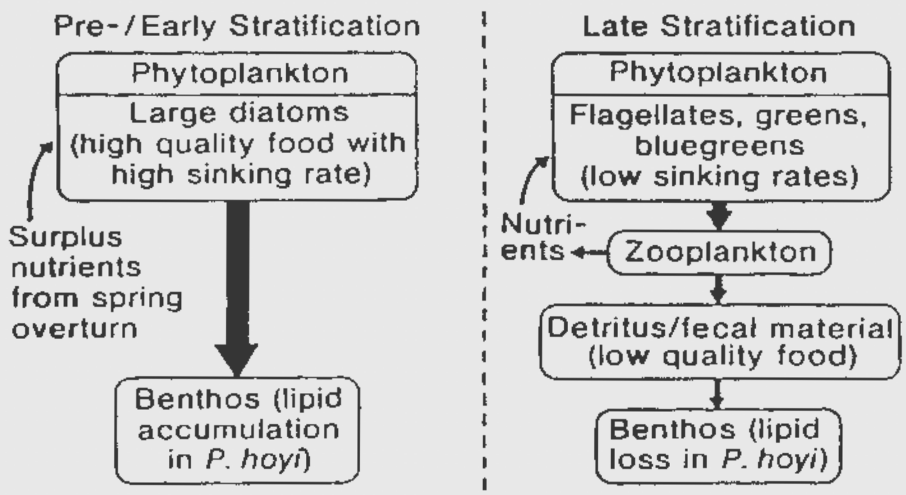


FIGURE 3. Schematic diagram of a conceptual model of the predominant processes for energy flow from phytoplankton to the benthos during (left) the pre/early stratification period (right) the late stratification periods, in southern Lake Michigan. (Figure 34.6, Gardner et al., 1990)

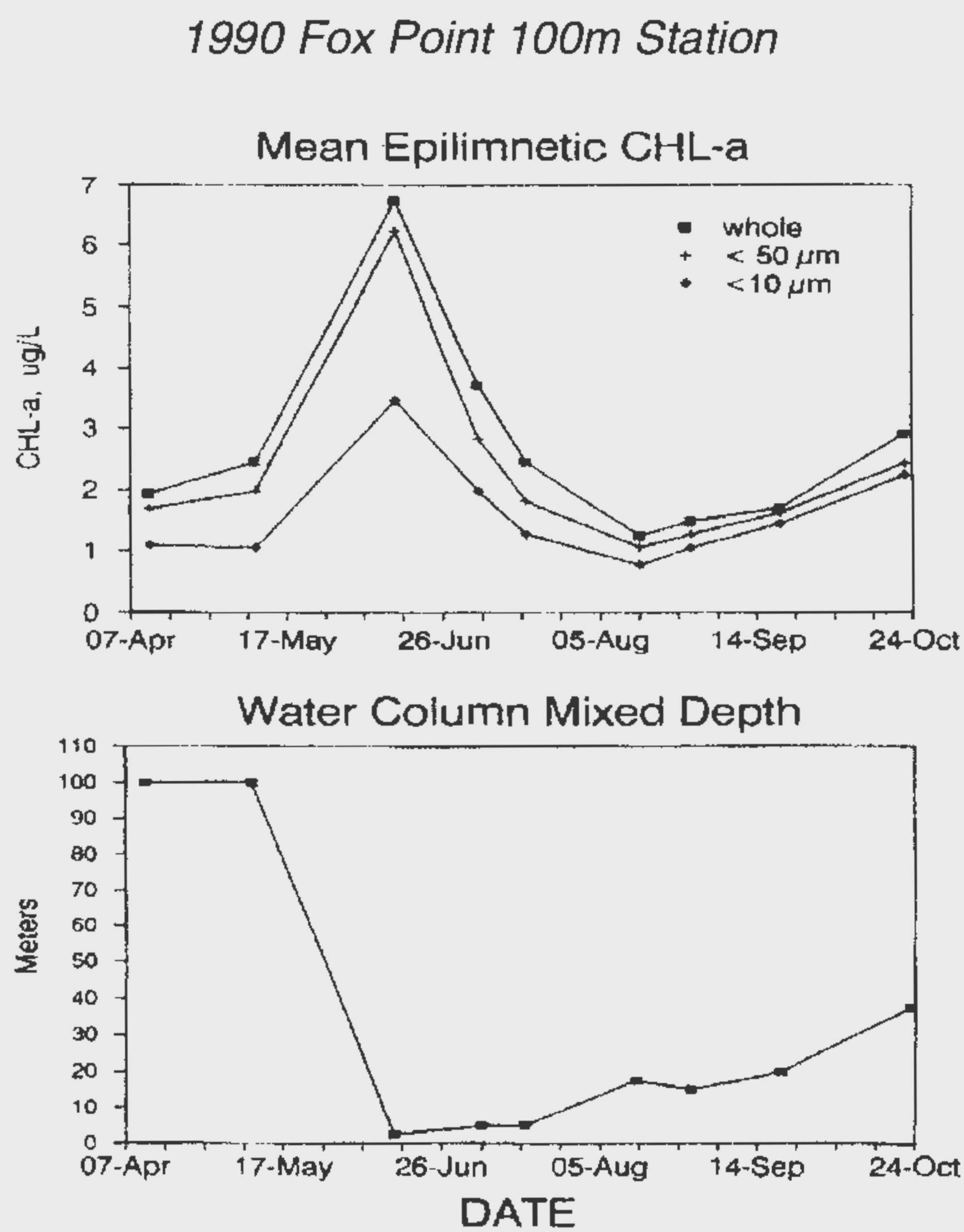


FIGURE 4. Unpublished data courtesy of Craig D. Sandgren.

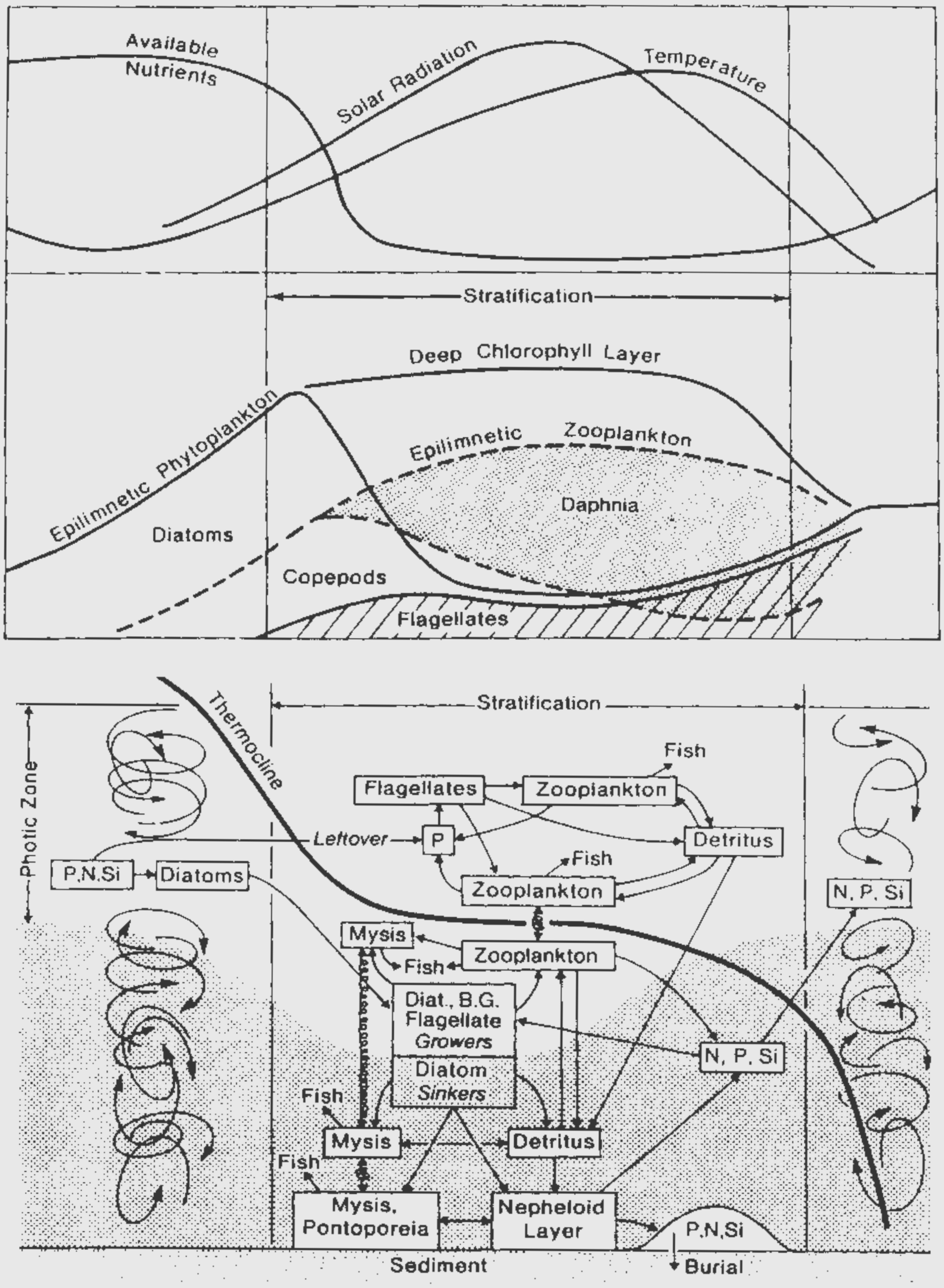


FIGURE 5. Schematic representation of the hypothesis for mechanisms controlling phytoplankton dynamics in Lake Michigan. (Figure 9, Scavia and Fahnenstiel, 1987)

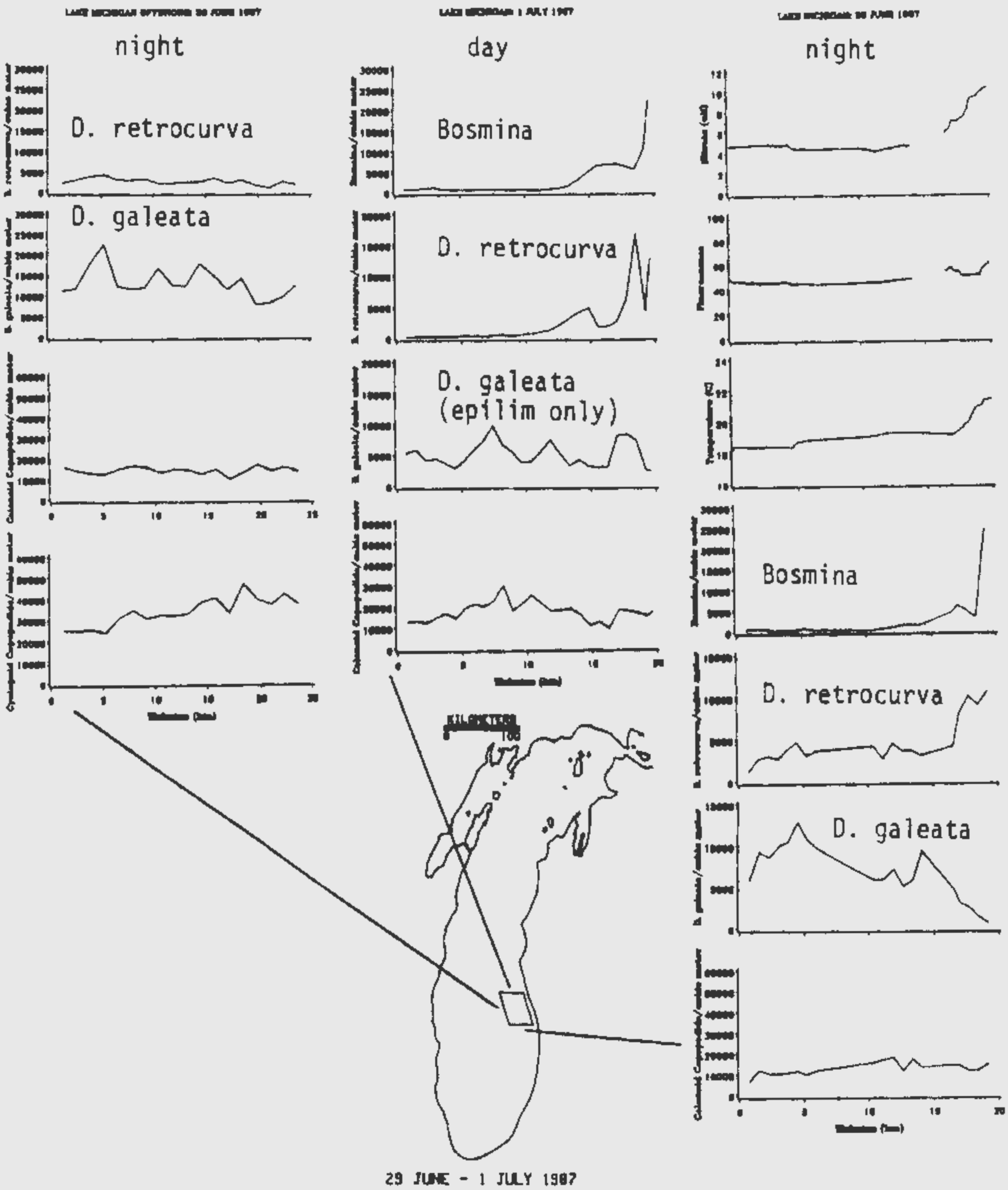


FIGURE 6. Horizontal gradients in species composition of epilimnetic zooplankton in Lake Michigan. Data from samples collected by towed submersible pump. Zooplankton samples were discharged through 130 μm plankton net, and samples were changed each 1 km. Note the high abundances of *Bosmina* and *Daphnia retrocurva* inshore, and the dominance of *D. galeata* offshore. (Lehman, 1991)

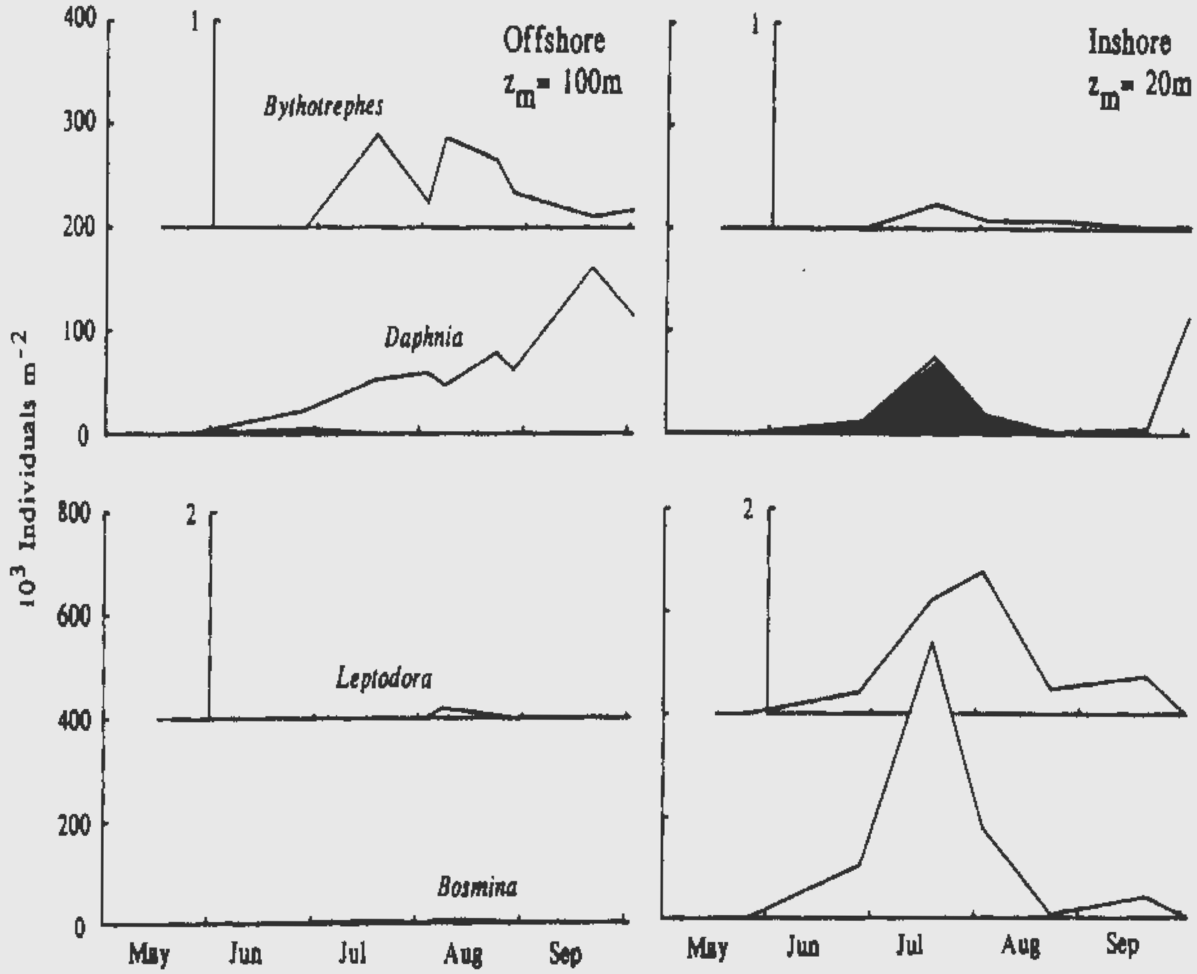


FIGURE 7. Seasonal abundances of cladoceran species at inshore and offshore locations 30 km. apart in Lake Michigan in summer 1989. Offshore station: 43° N, 86°40.0' W; inshore station: 43° N, 86°16.3' W. *Daphnia*: open - *D. galeata mendotae*; shaded - *D. retrocurva*. (Figure 5, Lehman and Caceres, 1993)

Appendix 3: Workshop Announcement and Call for Participation

Great Lakes Coastal Ocean Processes (CoOP) Workshop:
6-8 October, 1994 -- Milwaukee, Wisconsin

Deadline for Receipt of Applications is 1-Aug.-1994

CoOP is an interdisciplinary scientific program formulated to study basic scientific questions in the coastal ocean.* The goal of CoOP is to obtain a new level of quantitative understanding of the **processes** that dominate the transports, transformations and fates of biologically, geologically and chemically important matter over the continental margins, including the Great Lakes. The basic objectives of CoOP are to understand:

- The quantitative mechanisms, rates and consequences of cross-margin transport of momentum, energy, solutes, particulates and organisms
- The atmospheric and air-sea interaction processes that affect biological productivity, chemical transformations and cross-margin solute and particulate transport
- The roles of transport processes that couple the benthic and pelagic zones of the continental margin
- The nature, effects and fates of terrestrial inputs of solntes, particles and productivity in the coastal ocean
- The transformations of solutes, particulates and organisms across the continental margin

The goal of the Milwaukee workshop is to create a document that will define a possible CoOP process study in the Great Lakes. The envisioned field study must be fnlly interdisciplinary and focus on the CoOP program goals. The document should address needed modeling, specific choices (and motivations) for geographic locations and planned observations. The workshop report will delineate the important, CoOP relevant scientific problems to be addressed, develop a cohesive interdisciplinary approach to these problems, and establish priorities. The workshop is limited to 50-60 participants. Interested iudividuals should iudicate their willingness to participate in the workshop, including formulating, drafting and post-workshop editing of a science plan, by filling out the form below. Selection of iuvitees will be made by the workshop organizing committee in consultatiou with the CoOP steering committee based upon disciplinary and geographic expertise and balance. Iuvitees will be notified by 1-Sept.-1994.

Name (please print): ______________________________
Organization: ______________________________
Position: ______________________________
Business Address: ______________________________
City: ______________ State or Province: ____________ Zip: __________
Fax: (____)______________ Email:______________________

Please indicate your particular activities and research interests relevant toward participation in and contribution to this Workshop:

Please return to: Jane Hawkey, Horn Point Environmental Laboratory, University of Maryland, P.O. Box 775, Cambridge, MD 21613. Tel: 410-228-8200 x416 Internet: hawkey@hpel.umd.edu

Signature: ______________________________ Date: ______________
Telephone: Business: (____)__________________ Home: (____)______________

* The specific goals of CoOP are described in the CoOP Technical Report, *Coastal Ocean Processes: A Science Prospectus*. To obtain more information contact: Mike Roman, Horn Point Environmental Laboratory, Box 775, Cambridge, MD 21613 Omnet: M.ROMAN -- Internet: roman@hpel.umd.edu

---

Organizing Committee: Val Klump (Chair), Keith Bedford, Mark Donelan, Brian Eadie, Gary Fahnenstiel, Mike Roman
Host: Center for Great Lakes Studies, University of Wisconsin-Milwaukee

Appendix 4: Workshop Agenda

Great Lakes Coastal Ocean Processes (CoOP) Workshop

Milwaukee Art Center and War Memorial
750 North Lincoln Memorial Drive, Milwaukee, WI

Thursday October 6

8:30 am REGISTRATION - Memorial Hall, 2nd Floor

9:00 am WELCOME, CHARGE TO WORKSHOP
Val Klump, *Chair, Organizing Committee*

9:15 am THE CoOP PROGRAM
Mike Roman, *Chair, Steering Committee*

9:30 am OVERVIEW OF CROSS-SHELF TRANSPORT IN THE GREAT LAKES
Guy Meadows

10:15 am AIR-SEA INTERACTIONS IN THE COASTAL OCEANS
Mark Donelan

11:00 am BREAK

11:15 am WHAT DRIVES BIOLOGICAL PRODUCTION IN THE GREAT LAKES: LINKING THE PHYSICS AND CHEMISTRY TO THE BIOLOGY
Steve Brandt

12:00 pm SEDIMENT TRANSPORT AND PARTICLE DYNAMICS
Keith Bedford

12:45 pm LUNCH

2:00 pm THEME OF WORKING GROUP I BREAKOUT-
"PHYSICAL DYNAMICS OF COASTAL SYSTEMS AND THE RELATIONSHIP AMONG THE BIOLOGICAL, CHEMICAL AND GEOLOGICAL COMPONENTS":

- Coastal jets and alongshore transport processes
- Thermal fronts: vernal dynamics and structure
- Upwelling and stratified conditions
- Episodic events

5:15 pm HARBOR CRUISE with dinner buffet

Workshop Agenda (continued)

Friday October 7

8:30 am	GROUP I BREAKOUT - (continued)
10:00 am	BREAK
10:30 am	REPORTS OF WORKING GROUPS
12:30 pm	LUNCH
1:30 pm	THEME OF WORKING GROUP II BREAKOUT- "COUPLING MECHANISMS AFFECTING TRANSPORT, FATE AND TRANSFORMATIONS": ♦ Benthic-pelagic coupling ♦ Air-sea interactions ♦ Land margin effects ♦ Transformation of solutes, particles and organisms
5:30 pm	POSTER SESSION AND SOCIAL - University of WI, Center for Great Lakes Studies

Saturday October 8

8:30 am	GROUP II BREAKOUT - (continued)
10:00 am	BREAK
10:30 am	REPORTS OF WORKING GROUPS
12:30 pm	END OF GENERAL MEETING
2:00 pm	MEETING OF WORKSHOP ORGANIZING COMMITTEE AND WORKING GROUP CHAIRS AND RAPPORTEURS

Appendix 5: List of Attendees

David E. Armstrong
Water Chemistry Program
University of Wisconsin-Madison
660 N. Park Street
Madison, WI 53706-1484
608-262-0768
608-262-0454
armstron@engr.wisc.edu

Peter W. Barnes
U.S. Geological Survey
345 Middlefield Rd., MS 999
Menlo Park, CA 94025
415-354-3052
415-354-3191
pbarnes@octopus.wr.usgs.gov

Keith Bedford
Dept. of Civil Engineering
Ohio State University
2070 Neil Avenue
Columbus, OH 43210
614-292-6589
614-292-3780
kbedford@magnus.acs.ohio-state.edu

Pierre Biscaye
Lamont-Doherty Earth Observatory
Columbia University
P.O. Box 1000, Rte. 9W
Palisades, NY 10964-8000
914-365-8429
914-365-8155
biscaye@ldgo.columbia.edu

Susan E. Boehme
Institute of Marine & Coastal Sciences
Rutgers University-New Jersey
P.O. Box 231, Cook Campus
New Brunswick, NJ 08903-0231
908-932-6555 x235
908-932-8578
boehme@ahab.rutgers.edu

William Boicourt
Center for Environmental & Estuarine Studies
University of Maryland, HPEL
P.O. Box 775
Cambridge, MD 21613
410-221-8426
410-221-8490
boicourt@hpel.umd.edu

Tom Boyd
Ocean Science Division
National Science Foundation
4201 Wilson Blvd.
Arlington, VA 22230
703-306-1584
703-306-0390
tboyd@nsf.gov

Stephen B. Brandt
Great Lakes Center
Buffalo State College
1300 Elmwood Avenue
Buffalo, NY 14222
716-878-4329
716-878-4009
brandtsb@snybufaa.cs.snybuf.edu

Kenneth Brink
Dept. of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
508-548-1400 x2535
508-457-2181
kbrink@whoi.edu

Arthur S. Brooks
Center for Great Lakes Studies
University of Wisconsin-Milwaukee
600 E. Greenfield Avenue
Milwaukee, WI 53204-2944
414-382-1704
414-382-1705
abrooks@alpha1.csd.uwm.edu

Bruce Brownawell
Marine Sciences Research Center
State University of New York
Stony Brook, NY 11794-8820
516-632-9411
516-632-8820

Erik Christensen
Dept. of Civil Engineering and Mechanics
University of Wisconsin-Milwaukee
P. O. Box 784
Milwaukee, WI 53201
414-229-4968
414-229-6958
erc@watt.cae.uwm.edu

James Cotner
College of Agriculture and Life Sciences
Dept. of Wildlife and Fisheries Sciences
Texas A&M University
College Station, TX 77843-2258
409-845-4096
409-845-4096
jbc478a@tamvm1.tamu.edu

Russell L. Cuhel
University of Wisconsin-Milwaukee
Center for Great Lakes Studies
600 E. Greenfield Avenue
Milwaukee, WI 53204
414-382-1711
414-382-1705
rcuhel@csd.uwm.edu

Mark Donelan
Canada Centre for Inland Waters
National Water Research Institute
P.O. Box 5050
Burlington, Ontario Canada L7R 4A6
905-336-4879
905-336-4989
mark.donelan@cciw.ca

Clive Dorman
Dept. of Geological Sciences
San Diego State University
San Diego, CA 92182
619-594-5707
619-594-4372
clive@coast.ucsd.edu

Paul V. Doskey
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439
708-252-7662
708-252-5498
paul_doskey@gmgate.anl.gov

Brian J. Eadie
GLERL
NOAA
2205 Commonwealth Blvd.
Ann Arbor, MI 48105
313-741-2281
313-741-2055
eadie@glerl.noaa.gov

John Eise
National Weather Service
NOAA
N3533 Hardscrabble Road
Dousman, WI 53118-9409
414-965-2197
414-965-4296
jeise@smtpgate.ssmc.noaa.gov

Gary Fahnenstiel
GLERL
NOAA
1431 Beach Street
Muskegon, MI 49441
313-741-2275
313-741-2055
fahnenstiel@glerl.noaa.gov

Everett J. Fee
Freshwater Institute
501 University Crescent
Winnipeg, Manitoba
Canada R3T 2N6
204-983-5172
204-984-2404
Everett_Fee@fwi.dfo.ca

Sharon Fitzgerald
U.S. Geological Survey
6417 Normandy Lane
Madison, WI 53719
608-276-3816
608-276-3817
safitzge@maildwimdn.er.usgs.gov

Dave Folger
Atlantic Marine Geology
U.S. Geological Survey
348 Woods Hole Rd.
Woods Hole, MA 02543
508-457-2234
508-457-2310
dfolger@nobska.er.usgs.gov

Wayne S. Gardner
GLERL
NOAA
2205 Commonwealth Boulevard
Ann Arbor, MI 48105
313-741-2269
313-741-2055
gardner@glerl.noaa.gov

Hans C. Graber
RSMAS
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149-1098
305-361-4935
305-361-4701
hans@kiowa.rsmas.miami.edu

Ted Green
University of Wisconsin-Madison
Civil & Environmental Engineering
1261C Engineering Hall
Madison, WI 53706-1691
608-262-0038
608-262-5199
green@engr.wisc.edu

Nathan Hawley
GLERL
NOAA
2205 Commonwealth Boulevard
Ann Arbor, MI 48105
313-741-2273
313-741-2055
hawley@glerl.noaa.gov

Susan Henrichs
Institute of Marine Science
University of Alaska
Fairbanks, AK 99701
907-474-7807
907-474-7204
henrichs@ims.alaska.edu

Barbara Hickey
School of Oceanography, WB-10
University of Washington
Box 357940
Seattle, WA 98195
206-543-4737
bhickey@u.washington.edu

Randall Hicks
Dept. of Microbiology
Michigan State University
Giltner Hall
E. Langsing, MI 48824
517-432-1140
517-353-8957
hicksra@pilot.msu.edu

Bruce Jaffe
Pacific Marine Geology
U.S. Geological Survey
MS 999, 345 Middlefield Rd.
Menlo Park, CA 94025
415-354-3108
415-354-3191
bjaffe@octopus.wr.usgs.gov

Thomas C. Johnson
Large Lakes Observatory
University of Minnesota
Duluth, MN 55812
218-726-8128
218-726-6979
tcj@d.umn.edu

Bryan Kerman
Atmospheric Environment Service
Canada Centre for Inland Waters
867 Lakeshore Road
Burlington, Ontario Canada L7R 4A6
905-336-4798
905-336-4797
bryan.kerman@cciw.ca

Val Klump
Center for Great Lake Studies
University of Wisconsin-Milwaukee
600 E. Greenfield Avenue
Milwaukee, WI 53204
414-382-1700
414-382-1705
vklump@csd.uwm.edu

Douglas S. Lee
National Undersea Research Center
U of CT, Dept. of Marine Sciences
1084 Shennecossett Road
Groton, CT 06340-6097
203-445-3448
203-445-2969
dslee@uconnvm.uconn.edu

John T. Lehman
Dept. of Biology
University of Michigan
4121 Natural Science Building
Ann Arbor, MI 48109-1048
313-763-4680
313-747-2465
john.t.lehman@um.cc.umich.edu

Wilbert Lick
Dept of Mechanical Engineering
University of California-Santa Barbara
Santa Barbara, CA 93106-5070
805-893-4295
805-893-8651
willy@ferkel.ucsb.edu

Mark R. Loewen
Dept. of Mechanical Engineering
University of Toronto
5 King's College Road
Toronto, Ontario Canada M5S 1A4
416-978-1282
416-978-7753
loewen@me.utoronto.ca

Sally MacIntyre
Marine Science Institute
University of California-Santa Barbara
Santa Barbara, CA 93106-6150
805-893-2363
805-893-8062
sally@seaotter.ucsb.edu

Gerald Matisoff
Dept. of Geological Sciences
Case Western Reserve University
10900 Euclid Avenue, AW Smith #112
Cleveland, OH 44106-7216
216-368-3677
216-368-3691
gxm4@po.cwru.edu

Philipp Mayer
Center for Great Lake Studies
University of Wisconsin
600 E. Greenfield Avenue
Milwaukee, WI 53204
414-382-1700
414-382-1705
pmayer@csd.uwm.edu

Guy A. Meadows
Coop. Inst. for Limno.& Ecosys. Research
University of Michigan
IST Building, North Campus
Ann Arbor, MI 48109-2145
313-764-5235
313-936-8820
Guy_Meadows@um.cc.umich.edu

Russell Moll
CILER
National Science Foundation
4201 Wilson Blvd., Room 725
Arlington, VA 22230
703-306-1587
703-306-0390
rmoll@nsf.gov

Raj Murthy
National Water Research Institute
Canada Centre for Inland Waters
867 Lakeshore Rd., P.O.Box 5050
Burlington, Ontario Canada L7R 4A6
905-336-4920
905-336-4989
u084@cciw.ca

Siavash Narimousa
Dept. of Mechanical Engineering
University of Southern California
University Park
Los Angeles, CA 90089-1453
213-740-0499
213-740-8071
narimous@mizar.usc.edu

Joseph Niebauer
Institute of Marine Science
University of Alaska
Fairbanks, AK 99775-1080
907-474-7832
907-474-7204
niebauer@ims.alaska.edu

Hans W. Paerl
Institute of Marine Sciences
University of North Carolina
Morehead City, NC 28557
919-726-6841
919-726-2426
hpaerl@uncvx1.oit.unc.edu

Tom Powell
Dept. of Integrative Studies, Z001
University of California-Berkeley
Berkeley, CA 94720-3140
510-642-7455
510-643-6264
zackp@violet.berkeley.edu

Mike Reeve
Ocean Science Division
National Science Foundation
4201 Wilson Blvd.
Arlington, VA 22230
703-306-1582
703-306-0390
mreeve@nsf.gov

Charles C. Remsen
Center for Great Lakes Studies
University of Wisconsin-Milwaukee
600 E. Greenfield Avenue
Milwaukee, WI 53204
414-382-1700
414-382-1705
ccremsen@csd.uwm.edu

Dale M. Robertson
U.S. Geological Survey
6417 Normandy Lane
Madison, WI 53719
608-276-3867
608-276-3817
dzrobert@maildwimdn.er.usgs.gov

Michael R. Roman
Center for Environmental & Estuarine Studies
University of Maryland, HPEL
P. O. Box 775
Cambridge, MD 21613
410-221-8425
410-221-8490
roman@hpel.umd.edu

Craig D. Sandgren
Center for Great Lakes Studies
University of Wisconsin-Milwaukee
P.O. Box 413
Milwaukee, WI 53201
414-382-1700
414-382-1705
sandgren@csd.uwm.edu

Lawrence P. Sanford
Center for Environmental & Estuarine Studies
University of Maryland, HPEL
P. O. Box 775
Cambridge, MD 21613
410-221-8429
410-221-8490
sanford@hpel.umd.edu

James Saylor
GLERL
NOAA
2205 Commonwealth Boulevard
Ann Arbor, MI 48105
313-741-2118
313-741-2055
saylor@glerl.noaa.gov

Rich Signell
Atlantic Marine Geology
U.S. Geological Survey
348 Woods Hole Dr., Quissett Campus
Woods Hole, MA 02543-1598
508-548-8700
508-457-2310
rsignell@nobska.er.usgs.gov

Robert L. Smith
College of Oceanography
Oregon State University
Oceanography Administration Bldg. 104
Corvallis, OR 97331-5503
503-737-2926
503-737-2064
rsmith@oce.orst.edu

Richard Sternberg
School of Oceanography, WB-10
University of Washington
Seattle, WA 98195
206-543-0589
206-685-3354
rws@ocean.washington.edu

Rudi Strickler
Center for Great Lakes Studies
University of Wisconsin-Milwaukee
600 E. Greenfield Avenue
Milwaukee, WI 53204
414-382-1740
414-382-1705
jrs@convex.csd.uwm.edu

Clyde Sweet
Illinois State Water Survey
2204 Griffith Drive
Champaign, IL 61820-7495
217-333-7191
217-333-6540
csweet@uiuc.edu

Eugene A. Terray
Applied Ocean Physics & Engineering
Dept. AOPE, 217 Bigelow
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
508-548-1400 x2438
508-457-2194
eterray@whoi.edu

Jim Waples
Center for Great Lakes Studies
University of Wisconsin-Milwaukee
600 E. Greenfield Avenue
Milwaukee, WI 53204
414-382-1740
414-382-1705
jwaples@csd.uwm.edu

Ian Walsh
Dept. of Oceanography
Texas A&M University
College Station, TX 77845
409-845-7521
409-845-6331
walsh@astra.tamu.edu

Mark Wimbush
Graduate School of Oceanography
University of Rhode Island
South Ferry Road
Narragansett, RI 02882-1197
401-792-6515
401-792-6728
markw@ono.gso.uri.edu

Leonard J. Walstad
Center for Environmental & Estuarine Studies
University of Maryland, HPEL
P. O. Box 775
Cambridge, MD 21613-0775
410-221-8477
410-221-8490
walstad@hpel.umd.edu

Thomas C. Young
Dept. of Civil and Environmental Engineering
Clarkson University
P. O. Box 5715
Potsdam, NY 13699-5715
315-268-4430
315-268-7636
tcyoung@clvm.clarkson.edu

Appendix 6: Poster Presentation Titles

- Concentrations of PAHs in air and precipitation samples collected near the Great Lakes. Clyde W. Sweet and Karen Harlin. Illinois State Water Survey.

- Statistical distribution of airborne PCB and pesticide concentrations measured at regional sites on the Great Lakes. Donald F. Gatz, Clyde W. Sweet, Ilora Basu and Karen Harlin. Illinois State Water Survey.

- Coastal ice processes and particulate entrainment in the Great Lakes. Peter Barnes. USGS Nutrient and herbivore regulation of summer primary production in Lake Michigan. Craig Sandgren and William Walton. Center for Great Lakes Studies, University of Wisconsin- Milwaukee.

- Physical, chemical and biological coupling in the nearshore hydrodynamic region of western Lake Michigan. Art Brooks and Craig Sandgren. Center for Great Lakes Studies, University of Wisconsin-Milwaukee

- *In situ* measurements of sediment-water chemical exchange rates in a freshwater estuary using an ROV deployed benthic chamber system (BESS). Rob Paddock, Pat Anderson, Dave Lovalvo, Don Szmania, Jim Waples and Val Klump. Center for Great Lakes Studies, University of Wisconsin-Milwaukee

- Carbon dioxide and oxygen in southern Green Bay. Jim Waples and Val Klump. Center for Great Lakes Studies, University of Wisconsin-Milwaukee.

- Nutrients, biomass and vigor in Green Bay plankton. Russell Cuhel. Center for Great Lakes Studies, University of Wisconsin-Milwaukee.

- AES Large Buoy: An opportunity for research. Bryan Kerman and Murray Charlton. NWRI, Canada Centre for Inland Waters, Burlington, Ontario, Canada.

Document Library

Distribution List for Technical Report Exchange

University of California, San Diego
SIO Library 0175C (TRC)
9500 Gilman Drive
La Jolla, CA 92093-0175

Hancock Library of Biology & Oceanography
University of Southern California
University Park
Los Angeles, CA 90089-0371

Gifts and Exchanges Library
Bedford Institute of Oceanography
P. O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2
Canada

Commander
International Ice Patrol
1082 Shennecossett Road
Groton, CT 06340-6095

NOAA/EDIS
Miami Library Center
4301 Rickenbacker Causeway
Miami, FL 33149

Library
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah, GA 31411

Institute of Geophysics
University of Hawaii, Library Room 252
2525 Correa Road
Honolulu, HI 96822

Marine Resources Information Center
Building E38-320
Massachusetts Institute of Technology
Cambridge, MA 02139

Library
Lamont-Doherty Earth Observatory
Columbia University
Palisades, NY 10964

Library
Serials Department
Oregon State University
Corvallis, OR 97331

Pell Marine Sciences Library
University of Rhode Island
Narragansett Bay Campus
Narragansett, RI 02882

Working Collection
Texas A&M University
Dept. of Oceanography
College Station, TX 77843

Fisheries-Oceanography Library
151 Oceanography Teaching Building
University of Washington
Seattle, WA 98195

Library
University of Miami, R.S.M.A.S.
4600 Rickenbacker Causeway
Miami, FL 33149

Maury Oceanographic Library
Naval Oceanographic Office
1002 Balch Blvd., Bldg. 1003 South
Stennis Space Center, MS 39522-5001

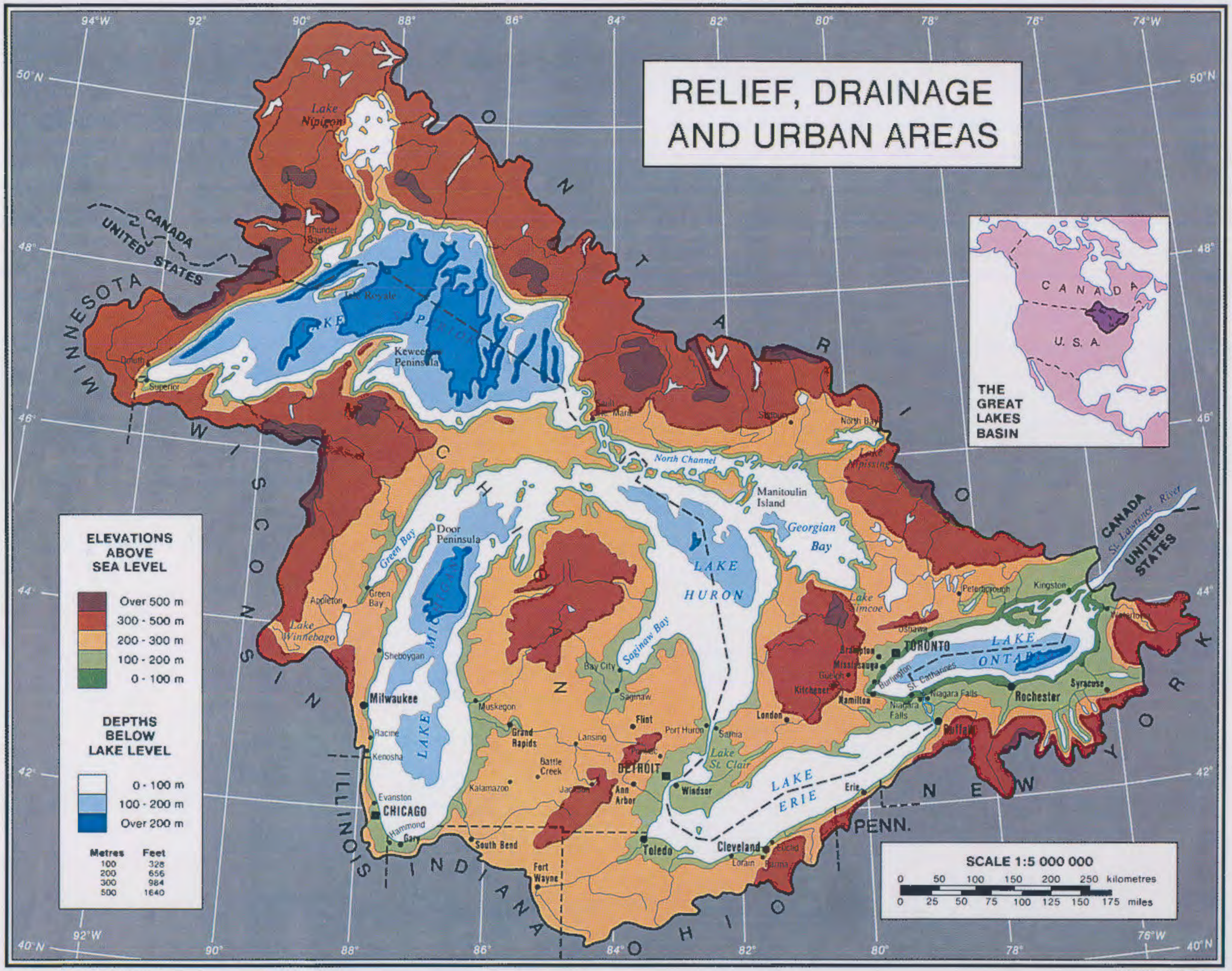
Library
Institute of Ocean Sciences
P. O. Box 6000
Sidney, British Columbia V8L 4B2 CANADA

Library
Institute of Oceanographic Sciences
Deacon Laboratory
Wormley, Godalming
Surrey GU8 5UB UNITED KINGDOM

The Librarian
CSIRO Marine Laboratories
G.P.O. Box 1538
Hobart, Tasmania AUSTRALIA 7001

Library
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, Merseyside L43 7RA
UNITED KINGDOM

IFREMER
Centre de Brest
Service Documentation-Publications
BP 70 29280 Plouzane FRANCE



Brock University Cartography